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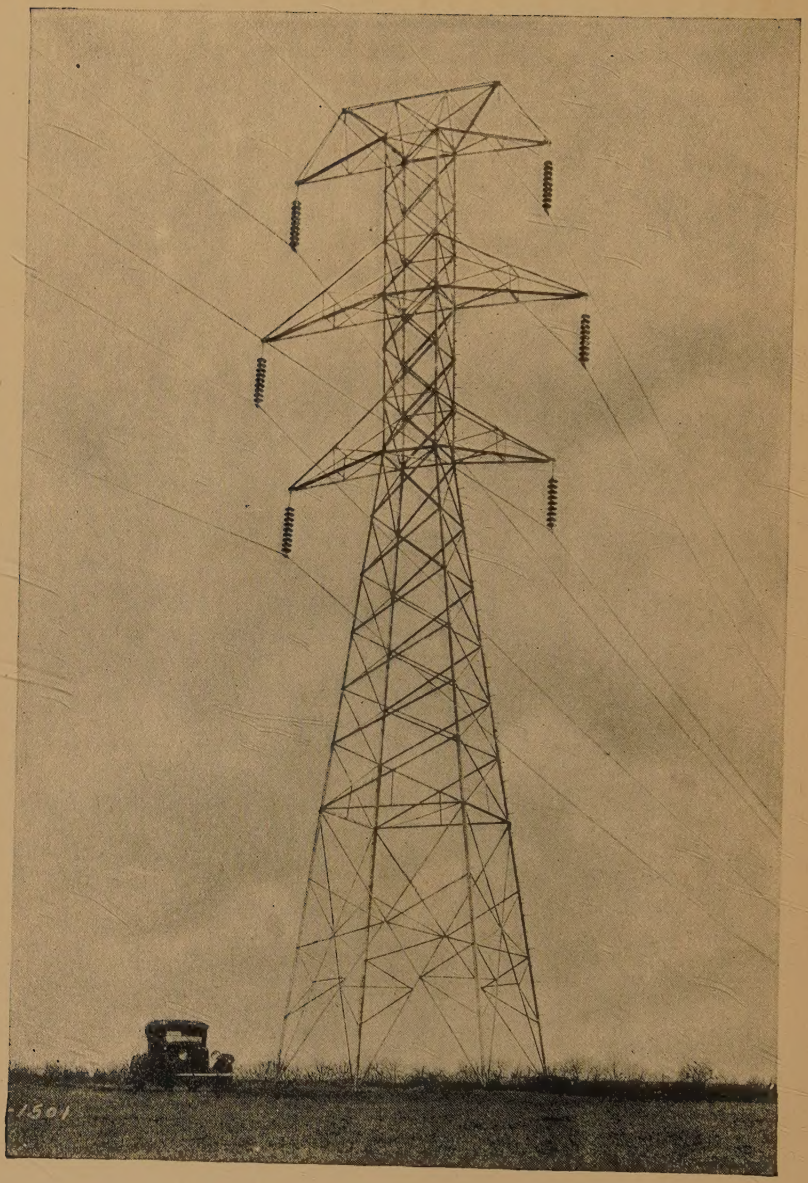

A Modern 132-kilovolt Transmission Line.

[*Frontispiece.*

HIGH TENSION LINE PRACTICE

MATERIALS AND METHODS

A Treatise on the Mechanical Principles Involved in Designing and Constructing Modern Power Transmission Lines

BY

ERNEST V. PANNELL

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NEW YORK
D. VAN NOSTRAND COMPANY
EIGHT WARREN STREET
1926

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Printed in the U. S. A.

LANCASTER PRESS, INC.
LANCASTER, PA.

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INTRODUCTION

RAPID and progressive development of the world's sources of energy is leading to great advances in the art of power transmission. Not only is the power of waterfalls more and more remote being brought into the cities, but steam and water power stations are being linked together in conglomerate networks, so that the individual loads are interchanged and carried with greater economy due to the improved diversity and load factors. This function of interconnecting existing power systems is probably, at the present time, a more important duty of the high tension line than the linking of a remote waterfall with an industrial center. In both aspects of the subject, however, most careful study of the design elements and the construction problems of the line are essential because of the important influence of these factors on the cost of the line and the capitalization of the system as a whole. While the cost of power houses and substations can be reasonably well predicated, that of the transmission line, from its very nature, is susceptible of far less exact determination and although a modern high tension line may be run across two hundred miles of country at a cost of fifteen thousand dollars per mile, local and special conditions might lead to a figure more than fifty per cent. higher. It is therefore hardly an exaggeration to say that the economic success of modern widespread power systems is, to a marked degree, dependent on the engineers responsible for the survey, planning, design and construction of the high tension lines.

In this work the attempt is made to record the present status of an art which is advancing so fast that it is difficult for its accompanying literature to keep pace. It is thought wise to treat of Materials (Conductors, Insulators and Supports) in the first half of the book and of Methods (Design, Construction and Economics) in the latter portion. No attempt is made

to treat of the electrical design or of electrical problems except for such brief references as are necessary to explain certain elements of the mechanical design. Special attention has been devoted to such matters as the modern tendency toward high strength conductors of composite design, heavy duty insulators, steel tower design, the construction of long crossings and construction costs. These last are subject to all the criticisms usually evoked by the inclusion of particular cost figures for general analysis. Nevertheless the author believes that dollars and cents should always be kept in view in a study of this nature and furthermore suggests that, properly analyzed and corrected, such estimates and cost sheets have considerable value.

While it is realized that the present status of the high tension line is largely an American achievement, modern developments in France, Germany and other parts of Europe as well as in certain portions of the British Empire, are sufficiently noteworthy to justify reference to them. Where such foreign practice is at variance from that customary in the United States analysis of it will generally be found interesting. The intention is therefore that this book should be not so much an epitome of American practice as a survey of the general aspect of transmission line work in various countries.

It is perhaps prudent to mention that most engineering devices of value are the subject of letters patent and this will apply to much of the apparatus illustrated in this book.

Among the many good friends to whom the author must acknowledge his gratitude for much informatory assistance are: Mr. H. A. Barre (Southern California Edison Co.), Mr. W. C. Chappell (Electric Bond and Share Co.), Mr. A. B. Cudebec (Consulting Engineer, Paris), Mr. A. E. Davison (Hydro Electric Power Commission of Ontario), Mr. E. L. Gemmill (Walter Bates Steel Co.), Mr. W. T. Goddard (Canadian Porcelain Co.), Mr. Torsten Holmgren (Consulting Engineer, Stockholm), Mr. G. E. Honn (Pacific Coast Steel Co.), Mr. J. S. Lapp (Lapp Insulator Co.), Mr. H. Mori (Nihon Electric Power Co., Japan), Mr. J. D. Ross (City of Seattle Power Dept.).

In acknowledging the source of much recent informative matter on the subject of transmission line engineering, it would be unfair not to include certain of the technical journals, in particular the *Electrical World* of New York and the *Elektrotechnische Zeitschrift* of Berlin. Both of these publications have recognized the considerable importance of the subject and have devoted an appreciable part of their space to recording developments in modern practice.

THE AUTHOR

HIGH TENSION LINE PRACTICE

MATERIALS AND METHODS

CHAPTER I

CONDUCTORS

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THE three physical elements of a power transmission line are: (1) conductors, (2) insulators, and (3) supports; and it will not be disputed that the conducting element is the most important, not only in function, but also in cost. In a modern power line the bare cost of the wire may amount to 30 per cent. of the expenditure on the entire work, including all material, labor, and engineering. This fact alone justifies a careful study of the conductors in order to ascertain what economies might be effected by modifications in design.

Copper is, of course, the oldest and best known conductor of electricity in commercial use. Its general use makes it the standard of comparison, and all other conductors are rated according to the " equivalent copper " area and resistance. Chief among the advantages of copper are its extensive production, established price, and open market. The wide distribution of the metal is another factor in its favor.

For transmission line construction bare stranded wire is produced from the electrolytic grade, this form being highest in purity and electrical properties. Since the major part of the world's production originates in the Western United States, it may be interesting to treat briefly of the methods followed for production in that territory. The ore is either an impure hydrated oxide or a sulphide containing iron and other elements in preponderance. Native copper ores occurring in the Lake Superior district are well known as the source of Lake copper, but electrolytic copper is more widely used as a wirebar metal. The sulphide or oxide ores are roasted in a calcining furnace to drive off the water and to burn off the sulphur. In some cases this operation is performed in a reverberatory furnace, the combustion of the sulphur providing part of the heat required for melting. The resulting product is a matte which contains from 50 to 70 per cent. copper, and the remainder iron and sulphur. Charging the matte into a converter, the impurities are burned out by an excess of oxygen and blister copper is obtained, having a purity of about 99 per cent. Blister copper, however, is analogous to pig iron in that it is unsuitable for forging or working, and it is next charged into a reverberatory hearth, where, after the oxygen has been reduced, the metal is rabbled or puddled and finally poled with a green hardwood stick. The resulting product is tough pitch copper, which can be rolled or forged to the maximum extent. More generally, as indicated above, the metal is

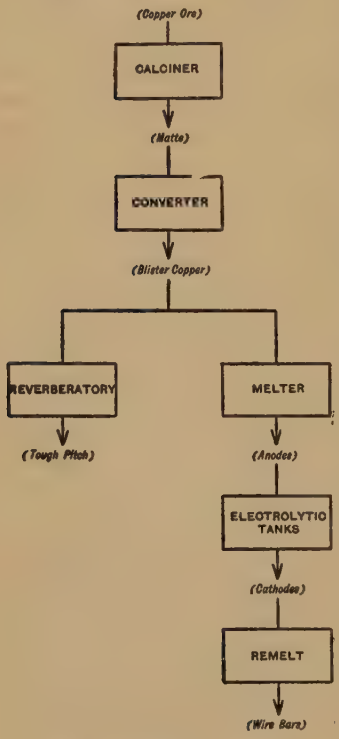


FIG. 1—Outline of copper production.

electrolytically refined, in which case the blister copper is cast into the form of anodes of approximately 3 feet square and 1 to 1½ inches thick. Anodes and cathodes are suspended alternately in the bath of copper sulphate and sulphuric acid, and in most refineries are connected in parallel. Continuous circulation of the electrolyte is secured, and a current density of about 16 amperes per square foot is maintained. During electrolysis impurities are separated out which could not otherwise be reached. Nickel, cobalt, iron, lead, and zinc dissolve in the electrolyte. Silver, gold, and platinum and other rare metals gravitate mechanically to the bottom of the tank, and are reclaimed from the mud together with cupric oxide, sulphide, and other compounds. Traces of bismuth, antimony, and arsenic will probably be deposited on the cathode. The purity of the metal is now at its maximum point, and it is only necessary to remelt and cast the cathodes into the conventional form of wirebar ready for the mill. In the United States the usual commercial wirebar is 225 lb. in weight, being about 50 inches long and 4 inches square, with pyramidal ends. In Europe wirebars are customarily some 40 per cent. lighter, but a wide range of sizes can be cast. Chilled iron moulds are used mounted on a rotating bed, which brings each in turn below the pouring outlet of the furnace. Electrolytic wirebars will generally approximate to the compositions given on page 4.

These figures are representative of the product of the largest refineries in the United States. Japan is one of the world's greatest producers, and wirebars from this country are closely in line with those from America, except that a somewhat higher proportion of antimony and arsenic is usually present.

Wire Manufacture.—Whilst the methods of manufacture outlined here relate specifically to copper, the broad principles are the same for all metals, the only exceptions being such details as number of rolling and drawing passes, reheating temperatures, and lubrication. In a typical large copper wire mill the wirebars are first pushed transversely into the reheating furnace, usually an oil-fired muffle, with double swinging flaps

at each end. Conveyor belts are not generally in favor, and the bars are pushed over the bed of the muffle by an air piston at the

TABLE 1.—*Analysis of Refined Copper Wirebars (United States Bureau of Standards).*

Sample	A	B	C	D
Copper	99.96	99.89	99.95	99.97
Silver	0.0027	0.0020	0.0018	0.0020
Arsenic	0.0060	0.0001	—	0.0001
Iron	0.0023	0.0028	0.0038	0.0044
Nickel	0.0030	0.0010	0.0028	0.0018
Oxygen	0.0191	0.0888	9.0315	0.0063
Lead	0.0024	0.0072	0.0010	0.0056
Antimony	—	0.0006	0.0009	0.0008
Selenium	—	0.0022	0.0026	0.0014
Sulphur	0.0026	0.0023	0.0026	0.0016

intake end. This piston works intermittently, so that about 100 bars per hour are handled, and each takes one hour to travel through the muffle. The actual temperature of the metal is 1,400° F. (750° C.), and immediately on exit the bar is passed through the hot mill in the following order:

(*a*) Roughing mill..... 7 passes
(*b*) Intermediate mill..... 5 "
(*c*) Finishing mill..... 6 "

Rolling speeds vary from 200 to 1,200 feet per minute. During rolling the shape of the bar is continuously changed from square to round in the roughing mill, whilst oval and round sections alternate in the intermediate and finishing passes, and a satisfactory high tensile strength wire depends almost entirely upon the correct design of the rolls in this regard. For the foregoing operations the finished rod or bolt will probably be 0.375 inch in diameter, or 0.111 square inch in section, and the average reduction in area for each of the eighteen passes is 5½ per cent. Rapidity of production is the object of most wire mills, and the operations here outlined, from billet to coiled rod, would consume forty-five seconds to one minute under commercial conditions. All rolls are three high, and in some

installations grooved channels or " repeaters " are used which automatically bring back and insert the rod through the appropriate hole.

It is customary to finish the rod or bolt with a diameter about 0.250 inch larger than that required for the finished wire. The remainder of the work is by cold drawing, but first it is necessary to remove the hard coating of scale or oxide which the rods have acquired in the mill. An acid dip is used for this purpose, after which the rods are rinsed in hot water and exhibit the characteristic clean salmon pink appearance. The copper oxide is recovered from the acid bath, and is in constant demand as a base for metallic paint.

Drawing is performed either upon individual and independent dies or blocks or upon continuous machines making from six to ten passes at one time. The use of either method is a question of production and size. For small orders of a variety of sizes and lengths individual blocks are best, but for a large output of any size of wire not larger than 0.125 inch the continuous machine will produce with a lower labor cost. As a compromise, it is becoming customary to gear up the speeds of the individual drawing blocks on a bench so that part of the advantage of continuous production is secured. In the production of transmission wire the rods are issued direct to the wire blocks without any further treatment, and for the production of a wire 0.080 inch from a rod 0.325 inch the following reduction would be given:

TABLE 2.—*Reductions for Copper Wire.*

			Reduction.
			Per cent.
Rod		0.325	
Pass No.	1	0.270	40
" "	2	0.232	35
" "	3	0.204	30
" "	4	0.182	25
" "	5	0.162	25
" "	6	0.144	25
" "	7	0.128	25
" "	8	0.114	25
" "	9	0.102	25
" "	10	0.091	25
" "	11	0.086	12
" "	12	0.080	12

Greater reductions than the above could be given without over-drawing, but the character of the product would probably not be as good.

It is hardly necessary to mention that these operations might be radically different in different mills; in fact, the practice in no two of them would be alike in detail. In some instances dies are of chilled iron, but steel are preferred in the majority of works, and are most useful in the long run, because of the ease with which they are upset and broached to size. Reductions are usually very heavy on the first four or five passes, and taper off as the finishing pass is approached, so that, beginning with a reduction of 40 per cent., the wire will finish with a 10 per cent. reduction, and the speed will vary in the inverse ratio from about 150 to 600 feet per minute. In the continuous machine rotating dies are used, and this practice achieves a good finish on the wire, eliminating grooves caused by a speck of scale becoming lodged in the die. Oscillating dies are sometimes used for the same purpose, but are a little less effective.

It is seldom that transmission wire needs annealing in the course of production, because the sizes most in demand can be finished direct from the rod without excessive work. If required to finish very small wire sizes or a medium hard temper, the material may be annealed at 1,100° F. (600° C.), and for this purpose the water-seal muffle is valuable, because it does not oxidize the copper nor burn and carbonize the grease on the surface of the wire. The finished product of the wire mill is tested for general appearance, tenacity, ductility, and electrical properties; in fact, acceptance tests are generally made at this stage as well as after the cable is stranded.

Stranded Conductors.—Little or no single wire is used for overhead transmission at the present day; the large sections employed, together with the necessity for great length, high tensile strength, and flexibility with satisfactory handling and operation, combine to render the use of stranded cable universal. This applies not only to copper, but also to steel, bronze, aluminum, and, in fact, every conductor material.

FIG. 2.—A MODERN NINE-DIE WIRE-DRAWING MACHINE (WATERBURY FARREL CO.).

[*Facing page 6.*

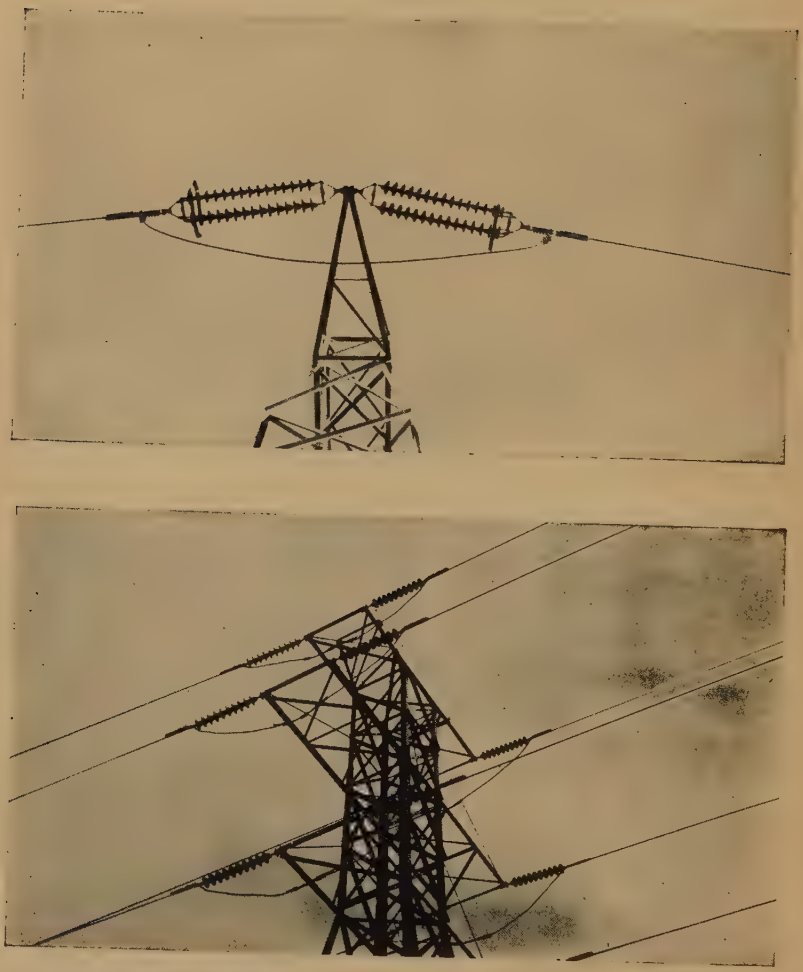


FIG. 3.—DEAD-END INSULATORS AS SEEN FROM BELOW. A DOUBLE YOKE ON A 220-KILOVOLT LINE AND SINGLE UNITS ON A 110-KILOVOLT SYSTEM.

[*Facing page 7.*

The operation of stranding is simple. For seven strands a high-speed strander can be used, and for larger cables a tandem strander, laying up eighteen or thirty-six wires at one time. The high-speed machine is generally in the form of a long steel tube, about 2 feet in diameter, mounted on bearings, and inside

TABLE 3.—*Stranded Copper Cables for Transmission (Standard Sizes).*

Area, square inches.			American circular mils.	Continental square millimeters.	Stranding.		
American.	British.	Continental.			American.	British.	Continental.
—	—	0.015	19,100	10	—	—	7 × 0.053
—	—	0.0248	31,600	16	—	—	7 × 0.067
—	0.025	—	31,800	16.1	—	3 × 0.104	—
0.026	—	—	33,100	16.8	7 × 0.069	—	—
0.033	—	—	41,742	21.3	7 × 0.077	—	—
—	—	0.039	49,600	25	—	—	7 × 0.083
0.041	—	—	52,634	26.4	7 × 0.086	—	—
—	0.05	—	63,600	32.2	—	3 × 0.147	—
0.052	—	—	66,373	33.5	7 × 0.097	—	—
—	—	0.054	68,800	35	—	—	7 × 0.098
0.066	—	—	83,694	42.5	19 × 0.066	—	—
—	0.075	—	95,500	48.3	—	3 × 0.180	—
—	—	0.078	99,200	50	—	—	7 × 0.118
0.083	—	—	105,534	53.5	19 × 0.074	—	—
—	0.100	—	127,100	64.5	—	7 × 0.136	—
0.1045	—	—	133,079	67.5	19 × 0.084	—	—
—	—	0.108	137,500	70	—	—	19 × 0.083
—	0.125	—	159,000	80.8	—	7 × 0.152	—
0.1318	—	—	167,805	85	19 × 0.094	—	—
—	—	0.140	178,000	95	—	—	19 × 0.098
—	0.150	—	191,000	90.5	—	7 × 0.166	—
0.166	—	—	212,000	107	19 × 0.106	—	—
—	0.175	—	223,000	113	—	7 × 0.180	—
—	—	0.186	236,000	120	—	—	19 × 0.110
0.196	—	—	250,000	127	37 × 0.082	—	—
—	0.200	—	254,000	129	—	7 × 0.193	—
0.2094	—	—	266,000	135	37 × 0.085	—	—
—	0.225	—	287,000	145	—	7 × 0.204	—
—	—	0.232	295,000	150	—	—	37 × 0.089
0.236	—	—	300,000	153	37 × 0.090	—	—
—	0.250	—	318,000	162	—	7 × 0.215	—
0.274	—	—	350,000	177	37 × 0.097	—	—
—	—	0.289	368,000	185	—	—	37 × 0.099
—	0.300	—	381,000	193	—	19 × 0.144	—
0.314	—	—	400,000	202	37 × 0.104	—	—
0.354	—	—	450,000	228	37 × 0.110	—	—
—	—	0.373	475,000	240	—	—	61 × 0.089
0.933	—	—	500,000	254	37 × 0.116	—	—
—	0.400	—	509,000	258	—	19 × 0.166	—
—	—	0.464	590,000	300	—	—	61 × 0.099
0.472	—	—	600,000	305	61 × 0.099	—	—
—	0.500	—	635,000	322	—	19 × 0.185	—

which the strand reels are mounted. The small diameter reduces the centrifugal forces, so that much faster production can be secured than with a conventional tandem strander, although the high-speed design is virtually limited to seven strands. Taking a single wire core, it will be seen that the number of wires which can be disposed around it in one layer is six; actually there is a little lost space, because the pitch circumference of the envelope is $2\pi d$ or $6.28d$. The next layer will be $4\pi d$ or $12.56d$, accommodating twelve wires. In some special cases the diameter of the core wire is reduced, so that there is no lost space in the envelope, but generally this practice would have no advantage. Succeeding layers of the envelope will have a number of strands lying in an arithmetical progression with a common difference of 6, so the complete cable will have seven, nineteen, thirty-seven, or sixty-one strands. As the most satisfactory size of wire to produce and handle is from 0.080 to 0.120 inch, the appropriate stranding for a given section is readily worked out. Special conditions sometimes call for cables having three or twelve strands, and sometimes for different shapes and sizes in the same conductor, but these are seldom required. (The subject of composite conductors will be treated later.)

In effect the stranded conductor partakes of the characteristics of a helical spring and it will be readily seen that the pitch of the helices will have an important effect on the properties of the stranded cable. In the first place the length of any wire in the envelope will be greater than the axial length of the core wire. If L is the axial length for one complete turn of the helix and D the pitch diameter of the helix then the actual length of the outer wire:

$$L_1 = \sqrt{L^2 + (\pi D)^2}$$

Experience has shown that for most stranded conductors a good ratio of L the axial length of lay to D the pitch diameter is 15.7. In other words if any wire in the envelope forms a helix with a pitch diameter of one inch such wire will occupy 15.7

inches in making a complete turn around the conductor. This stranding pitch leads to an excess length of L_1 over L of two per cent., so that for every wire except the core the weight and ohmic resistance will be two per cent. greater than that calculated from the axial length. For conductors of seven or nineteen strands there is a tendency to strand with a longer lay than that indicated a pitch ratio of 20 being commonly used. With an increasing number of strands however manufacturing limitations will reduce the ratio to the average value of 15.7 as already quoted. For special purposes conductors may be laid up with a still shorter pitch but occasion for this seldom arises.

The inclination of the wires to the axis involves the fact that, while the tension on a loaded cable is axial, the wires, with the exception of the core, are not axial. Loading will not be equally distributed over the section of all the wires, and the stress in the core will generally be slightly higher than in the envelope. The difference is small, however, and in a seven-strand cable the center wire is generally of a somewhat more ductile wire to compensate for this. It must be observed that the elongation of a stranded conductor is made up of two components:

(a) The ultimate elongation of the individual wires.
(b) The helical extension of the cable as a whole.

Factor (b) is indeterminate, but must not be neglected; meanwhile the core wire must be able to withstand an elongation of $a + b$, or an elastic extension of a proportionate amount. The use of a hemp core which will extend the maximum possible amount is not considered to be as good practice as the employment of a slightly annealed wire, already mentioned.

For electrical reasons, it is often desirable that the conductor should have an augmented diameter, and certain special types of stranding have been employed for this reason. On the Pacific coast considerable use has been made of a rope-stranded conductor of forty-nine strands, being virtually seven cables each of seven strands laid up together. Another method of producing

an increased diameter for a given section is to use a hollow core. It might seem a physical impossibility to lay up a conductor virtually on an air core, but the actual facts may be illustrated by considering a core in the shape of a long spiral spring or, more properly, a flexible metallic tube. From its nature, this core would be competent to carry but a very light load, but this is of little significance, since it forms only the framework for the annular envelope. Obviously, a hollow core of any reasonable diameter can be introduced, and a bulky conductor of light weight will result. Such a cable will be of value for high voltage or high frequency, as it will have a high discharge voltage and will be compensated for skin effect.

The mechanical problems of a stranded conductor under load have received very inadequate study. Friction between the individual wires is an indeterminate quantity, but must attain very high values on account of the tendency of the helices to straighten when under tension. Elastic modulus of a stranded cable appears to be appreciably lower than that of its component wires, due, no doubt, to the helical extension already mentioned, but it shows an increase the longer the stranding pitch, as well as after repeated loading. A study of cable construction will show that all mechanical properties vary with this lay, and that the true qualities of the wire are best realized with a long pitch. Ultimate strength and elongation are the only strictly determinable quantities; both should very nearly correspond with those for the component wires, unless a very short length be tested, in which case unequal distribution of load will give a low result. A profoundly interesting and valuable series of tests was made in 1922 at the National Physical Laboratory, London, under the direction of the British Electrical and Allied Industries Research Association, and cover single and stranded conductors of various materials. The following figures are abstracted from the results published in the Association Report:

TABLE 4.—*Tests on Stranded Copper Cables.*

(Test samples were in the form of a 300-foot horizontal length with axial loading.)

Number of strands	3	7	19	37
Diameter of strands (in.)	0.166	0.166	0.166	0.144
Area of cable (sq. in.)	0.0647	0.1512	0.4049	0.5983
Tensile strength* (lb. sq. in.)	58,400	58,400	60,000	61,000
Proportional limit (lb. sq. in.)	14,150	9,420	15,700	—
Modulus of elasticity (first loading)	16.8×10^6	17.1×10^6	16.0×10^6	15.5×10^6
" " " (fifth loading)	18.4×10^6	18.4×10^6	16.7×10^6	15.7×10^6

It is clear that the properties of a stranded cable depend very profoundly on the amount of load which has previously been applied, and for this reason it is unfortunate that the larger conductors in this test could be loaded only up to about one quarter their ultimate capacity. The same physical limitations prevented a record of the ultimate elongation or breaking load on a long cable. As to the ultimate tenacity of a cable, it is fair to assume from the tests that this will average some 5 per cent. lower than the sum of the individual wires, but as the ultimate figures were obtained only upon short lengths of cable, this percentage will be much less in practice.

In reference to the general subject of stranding, it will be seen from Table 3 that there is considerable divergence of practice in national standards. The tendency of British practice is to use the minimum number of individual strands in a cable, whilst in American practice a much larger number is used. On the Continent of Europe the tendency is to employ a compromise between the two. A conductor of around 100,000 circular mils will have three strands in British practice, seven strands in Continental, and nineteen in American practice.

There is a good argument in favor of maintaining the largest reasonable size of individual wire, because a slight surface injury or defect will not create an appreciable loss of strength. On the other hand a considerable degree of tensile strength is sacrificed by using wires larger than about 0.120, especially in

*Tensile strength figures were obtained on a single wire from the same shipment.

the case of aluminum, which shows the greatest variation of tensile strength.

There is also the matter of flexibility, and a cable consisting of heavy wires will be very stiff and difficult to handle in the field as compared with more flexible stranding. Greater care will have to be taken to prevent distortion of the former type of conductor, and it will require a larger diameter of reel to avoid permanent deformation.

FIG. 4—Outline of aluminum production.

Aluminum.—No study of transmission line practice would be complete if it considered only copper conductors, and, as a matter of fact, at least three or four other types of conductor are available, each of them having its own most appropriate sphere of use. Aluminum is, apart from copper, the oldest and most significant metal for wire production. In the stranded form it is widely used on some of the most important high tension systems.

Whilst aluminum is very widely distributed in the earth's crust in the form of kaolin and other siliceous compounds, it is so intimately associated with silica as to be most unprofitable to reduce from this form, and most of the aluminum is produced from bauxite and laterite, which, though less widely dispersed, yield a much more satisfactory product. Bauxite, after mining, is crushed and calcined, afterwards being treated with caustic soda under steam pressure (Bayer process). After precipitation and filtration, the residue is hydrate of alumina. This is calcined and electrolyzed at 1,650° F. (900° C.) in a bath of molten cryolite (double aluminum-sodium fluoride). Metallic aluminum is tapped in the form of pigs, which are graded, remelted in a reducing atmosphere, and poured into wirebars similar in shape to those of copper, but, because of the relative densities involved, only one third of the weight.

Purity of aluminum is commercially lower than that of copper, the principal impurities being iron and silicon. For wire bars the minimum purity of high conductivity aluminum

FIG. 5.—Autographic stress-extension curve for an aluminum wire, 0.135 inch.

would be 99.50 per cent., there being present about 0.30 per cent. iron and 0.20 per cent. silicon and other impurities. Slightly higher or lower purities than this may be employed, and the conductivity will vary to a slight extent. If the analysis shows less than 0.5 per cent. impurity, the mechanical strength of the wire will probably be low, and its working may offer some difficulty. To a certain degree conductivity depends upon working and treatment as well as upon analysis, and the resistance of hard-drawn wire will be found about 2 per cent. higher than if annealed.

Fabrication of wire and cable follows the same general lines as copper. Aluminum is reheated at 840° F. (450° C.), and rolled and drawn with similar speeds to copper, but with somewhat smaller drafts and more fluid lubricant. Annealing is seldom required, and no dipping is necessary on account of the absence of scale.

Compared with copper, a given section of aluminum wire will have 45 per cent. of the tensile strength, 60 per cent. of the conductivity, and 30 per cent. of the weight. However, in electrical design it is usual to compare on the basis of a given conductivity, in which event aluminum wire will have 75 per cent. the tensile strength, equal conductivity, 50 per cent. the weight, and 166 per cent. the volume of copper. With due regard to design, therefore, aluminum stranded wire can be, and is being, widely used for transmission lines, and only in recent years is it being superseded by a steel reinforced cable. Although aluminum wire must be larger than the equivalent copper, this is very seldom of serious moment, and the lighter weight affords adequate compensation. In handling the metal certain precautions are necessary, because of its lower tenacity, but aluminum wires are commonly drawn some 20 per cent. larger than copper. Because the modulus of elasticity is only 9 million as compared with 18 million for copper, the wire is nearly twice as flexible, and larger wires do not introduce stiffness. The resistance to corrosion was somewhat low in early installations, because of inferior purity, but is now superior to most other metals, as borne out by twenty years of experience with conductors strung on the sea coast, and also in coke-oven districts. On the other hand, chlorine or strongly alkaline vapors will tend to disintegrate the wire rapidly. Due to the high electrolytic potential of the metal and to the insolubility of its oxide coating, soldering is seldom a satisfactory process, and mechanical means are employed for all joints and connections which are cast or forged in pure aluminum. (The analogous practice is generally followed with copper wire for outdoor work.)

Bronze.—It is obvious that in transmission line work the tensile strength of the wire has a very profound influence on the economy of the line. The sag of the wires varies inversely as the tension to which they can be pulled up, and if the sag is reduced to the minimum, fewer or shorter poles or towers need to be used, and a very considerable saving can be brought about. Copper wire, when hard drawn, has a tensile strength of 55,000 to 60,000 lb. per square inch, and a maximum working tension of probably half this amount. For certain purposes, the introduction of a small percentage of tin and silicon or phosporus has been followed, thereby obtaining an ultimate strength of 70,000 lb. per square inch and, what is far more significant, an ultimate elongation of more than 3 per cent. on 10 inches. Unfortunately, this is accompanied by a reduction of nearly 40 per cent. in conductivity, and for that reason bronze wire cannot be seriously considered as a transmission conductor, except for special locations, where an exceptionally long span length may introduce mechanical problems far more important than the electrical one. The chief field of use for this class of conductor is for long river crossings, where navigation clearances require the cables to be pulled up to the flattest possible curve. In Germany several crossings of the Rhine and the Elbe are installed with silicon bronze wires for this reason. As a trolley wire silicon bronze is well known and approved; its good wearing qualities yield a much longer life than copper wire of equal weight.

A bronze of much higher strength than that quoted is now being proposed as a reinforcing core for composite copper-bronze cables. It has a tensile strength of 125,000 lb. per square inch, and a conductivity of 37 per cent. The possibilities for a conductor of this type appear very great.

An interesting example of the use of bronze wire is shown in a crossing of the Allegheny River by the transmission lines of the West Penn Power Co. The length of span is 1,450 feet, and the conductors used have an area of 0.19 square inch, being made up of thirty-seven strands silicon bronze wire, each 0.075

inch diameter. The ultimate strength of the cable is 15,050 lb., corresponding to a stress of 80,000 lb. per square inch, the maximum load in service being one half these figures.

Copper-clad Steel.—Instead of mixing an alloy, the tenacity of copper wire can be enhanced by introducing a core of steel. This has been very successfully accomplished in wire of the above title, and is commercially produced in several rolling mills. There are some differences of detail in the methods followed by different factories, but the principle involved is the same. It is first necessary to produce a composite cylindrical wire bar, for which purpose a steel billet is heated, dipped into molten copper and afterwards lowered into a vertical graphite mold, where copper is poured around it. In another process a film of copper is first deposited on the steel by electrolysis and a copper sleeve is then shrunk over it. It will be clearly seen that the essence of a successful product lies in the perfect adhesion of this film, in fact the object is stated to be the formation of a copper-iron alloy around which the copper can be cast. Careful design is necessary for the relative diameters of the core and annulus, because in fabrication the copper will be reduced at a somewhat greater rate than the steel. Hot rolling and cold drawing follow the usual chain of operations, and the finished wire is available in several grades, of which the "40 per cent." is most commonly used as a conductor. This phrase denotes that the wire has approximately 40 per cent. the conductivity of the equivalent solid copper rod, or briefly, that the copper area is 40 per cent. and the steel 60 per cent. of the entire wire. Other grades of 30 per cent. and 60 per cent. conductivity are also produced. In the 40 per cent. grade the diameter of steel core is 75 per cent. of the total diameter, and from this it is seen that the copper sheath may become very thin in small sizes of wire. The obvious practice is to maintain a reasonable minimum size, otherwise a very slight eccentricity may cause the copper to split and to peel right off the steel. With this precaution, some important installations have been made, involving long river crossings in excess of 2,000 feet.

As in the case of bronze wire, the scope of copper-clad steel is necessarily limited by reason of its low conductivity, and if wires are compared on this basis the copper-clad must be two

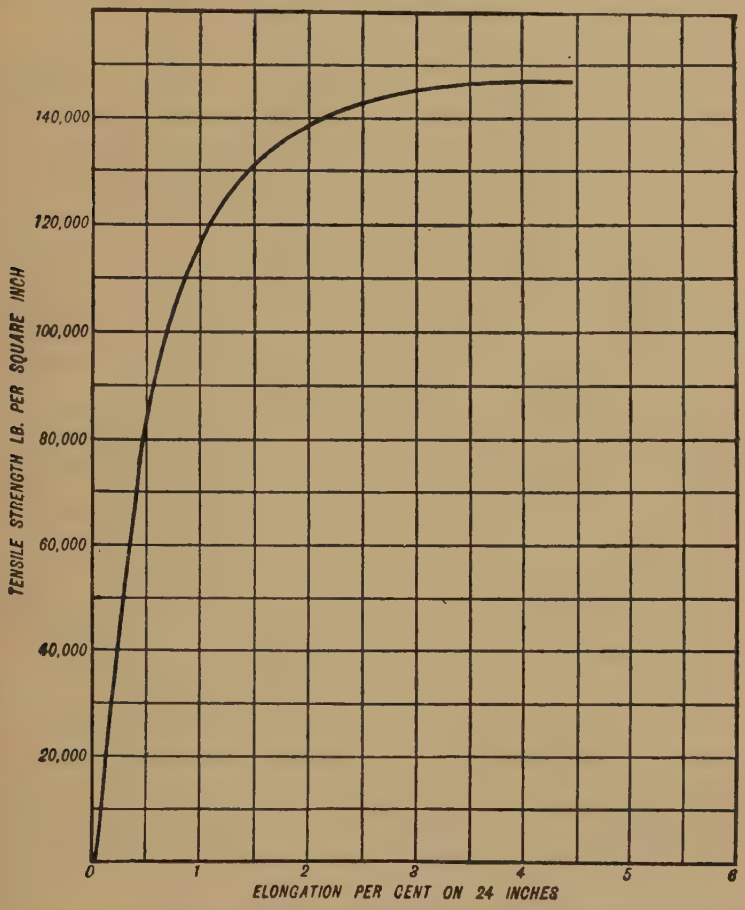


FIG. 6.—Characteristic curve for copper-clad cable. Size 7 by 0.106 (79,000 cir. mils); maximum stress, 147,000; yield point, 70,000 lb. square inch; elongation, 4½ per cent. on 24 inches.

and a half times as heavy as copper. Nevertheless, as already seen, there are many installations where high tenacity is more important than conductivity, and in this case the high ultimate figure of 90,000 lb. per square inch is of value. For rural

feeder and telephone lines the conductivity of wire is sometimes of little importance, and copper-clad steel offers the most economical practice because it enables poles to be spaced more widely. Although for the run of the main transmission lines copper-clad steel cables would be too heavy, there is a practical possibility of reinforcing a copper cable by using a copper-clad core, in this way compromising between copper and copper-clad to any desired extent. The distribution of mechanical load in such composite cables will be treated later, but it may be said that the disadvantage of possible corrosion between wires of different metal (such as copper and galvanized steel) is eliminated in the present case, because the copper sheath forms a most effective protection to the steel and, of course, makes external contact only with copper.

An illustration of this is seen in a crossing of the Cheat River, near Beaver Hole, in West Virginia. (See p. 217.) The span length is 4,317 feet, which is among the six longest on record and, necessarily, a conductor of special characteristics must be used to maintain the requisite clearances. The actual conductor used is a composite one, consisting of nineteen strands, the center seven being of a high strength, copper-clad, and the outer twelve being of copper. Each wire has a diameter of 0.106 inch, giving 0.530 for the diameter of the cable. Weight per foot is 646 lb., and the ultimate strength of the conductor is 15,000 lb. A stranded copper conductor of the same size would carry a tension of little over 9,000 lb. under the same conditions, and the sag would be 60 per cent. greater. Obviously, therefore, this reinforced conductor has considerable economic value in requiring supports of the minimum height with shorter cross arms.

Aluminum Alloy.—As already indicated, aluminum has the lowest tenacity of any material used as a conductor, and the consequent sag sometimes results in a somewhat greater construction cost of the transmission line as a whole. The lower cost of the wire may compensate for this, but generally, there would be a distinct economic advantage if the tensile properties

of the wire were not so low. Aluminum can be alloyed with other elements (notably manganese or nickel) and drawn into wire of very much improved characteristics. Certain installations in Europe (notably the Hagfors-Forshult transmission in Norway and part of the Trollhattan power system in Sweden) are strung with aluminum alloy wire on their long spans, thereby reducing the sag to the minimum. Such an alloy as this would have a tensile strength of 40,000 lb. per square inch, or more than 60 per cent. in excess of hard-drawn pure aluminum. Whilst this figure is relatively low as compared with copper, the significant factor in wire calculations is the ratio of tensile strength to weight and in the case of copper, this figure might be arbitrarily assumed at unity, then for aluminum wire it would be 1.38 and for alloy wire 2.10. On the other hand, a conductivity of 50 per cent., the equivalent copper, would probably be the maximum attainable. Another circumstance which has never been thoroughly attested is the relative deterioration of alloys. Some instances of exposure to weather resulted in rapid corrosion, manifested in deep local pitting. So far as the evidence goes, all such alloys contained copper in addition to aluminum, a combination which is distinctly unsatisfactory under exposure. It may be found, however, that aluminum manganese or aluminum nickel alloy wire is relatively immune from such action, and a number of other binary combinations are practicable which would offer high tenacity, ductility and corrosion resistance.

Recent developments in Europe, especially in France, involve the use of an aluminum alloy wire containing about 1 per cent. magnesium and the remainder aluminum. This alloy is believed to be not only extremely light and resistant to corrosive atmosphere but its conductivity is very little inferior to that of pure aluminum.

A series of very interesting tests of long duration has been reported by Dr. Ernest Wilson of Kings College, London, England. In these experiments a group of wire samples was made up containing aluminum alloyed with small percentages

of copper, nickel, manganese and zinc and these have been exposed to the weather since the year 1901, periodical tests having been made of their physical and electrical properties. In this way the deterioration due to atmospheric conditions in a large industrial city have been shown up in very striking manner and the great superiority of certain of the samples over others affords some most valuable conclusions. Both pure copper and pure aluminum show a certain amount of deterioration.

The most noteworthy of the alloys in its behavior under this long-continued exposure was that containing 2.3 per cent. nickel, the balance being aluminum with a small percentage of copper. Relatively small deterioration both in conductivity and physical qualities is noted and the result would probably have been still better had an alloy of aluminum-nickel been used without any admixture of copper.

A wide field exists for development work, and the subject cannot be regarded as being yet in the commercial stage.

Steel.—Although iron and steel have both high resistance and magnetic properties which prejudice their use as conductors, they cannot be entirely neglected. In the first place, steel is the metal produced in the greatest abundance, and during the metal famine of the war period many miles of steel transmission wire were erected, and the practice showed signs of permanence. In many systems the size of wire is not determined by the load, but by mechanical reasons alone, and the low cost of steel wire was sufficient argument for its use. The reason why the practice has not been perpetuated was not because of high resistance or reactance, as all necessary allowances were made in the design, but because the deterioration of the wire made too heavy a demand upon the maintenance department. It is generally conceded to be very difficult to maintain galvanizing intact on a steel wire during long exposure, and it has been found necessary in certain important installations to paint the wire periodically with red lead. Although the disadvantages of steel wire for regular transmission practice are somewhat serious, there are some notable installations where it is difficult to imagine what

could have been done without high tenacity steel. Six wires are installed across Carquinez Strait, in California, a distance of 4,427 feet clear, between supports over a tidal estuary, with a

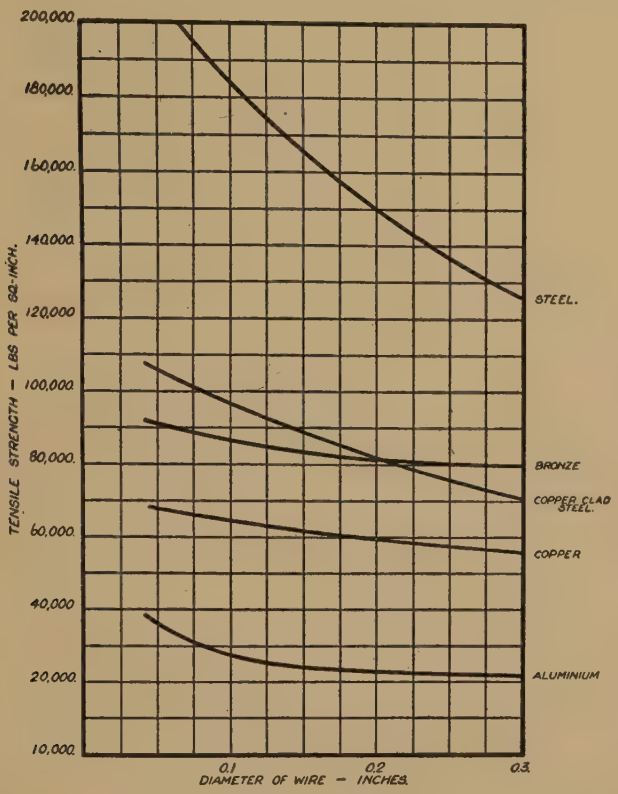


FIG. 7.—Tensile strength of different conductor wires.

minimum clearance of 206 feet. Conductors are nineteen strands of 0.175 inch steel wire. Another long crossing is on the St. Lawrence, near Three Rivers, Quebec, where a width of 4,801 feet is also spanned by steel cables. (See p. 215.)

Future developments will assuredly lead to longer spans where straits and rivers have to be crossed and high carbon or chrome steel wire must be adopted to make such crossings possible. On the other hand, standard transmission line construction is not economically the best place to use steel or iron wire.

Aluminum-Steel.—In treating of aluminum wire it was intimated that this material was only at a disadvantage because of its relatively low tenacity. Any device which would compensate for or increase this factor would be of value and of several such devices the use of a steel wire core has been proved the most effective. Such composite conductors of aluminum and steel have been in use since the year 1910, and are now standard on probably half the long-distance transmission systems in America, as well as being widely used in France, Ger-

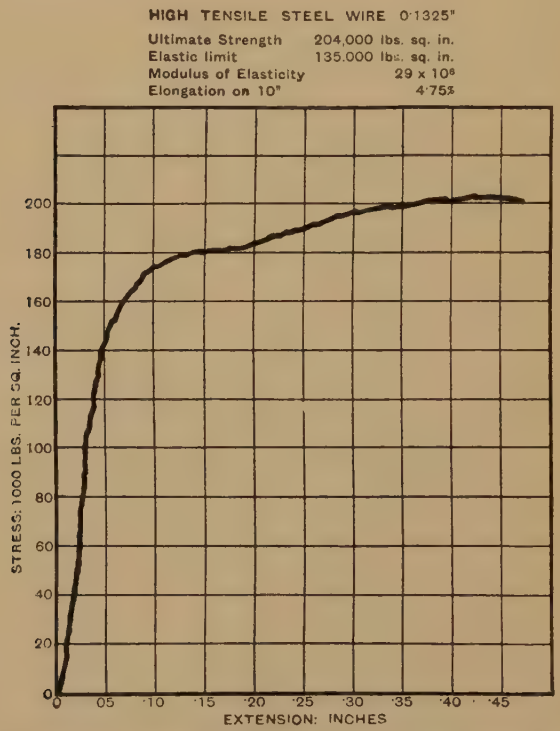


FIG. 8.—Autographic stress-extension curve for a high tensile steel wire, 0.1325 inch.

many and Sweden. The simplest form of such a conductor provides a single steel wire around which are laid six strands of aluminum. Mechanical characteristics therefore become a compromise between those of the two metals, allowing for the fact

that 14 per cent. of the total area is steel and 86 per cent. aluminum. Broadly, the tensile strength is improved by 80 per cent. over that of aluminum cable, the weight at the same time is increased 50 per cent. Although the situation in respect of stress and extension might appear to be complex, there is in practice complete harmony so long as proportional limits are not exceeded. On its general merits and by virtue of its wide adoption, this class of conductor would seem to be at least in the same class as copper.

Theodore Varney, in a valuable study of the subject, makes the following reference to the type of steel wire in use for reinforcement.

> "In the form of wire the highest tensile strength per unit cross section is obtained at the present time with high carbon steel. Special alloy steels would perhaps give higher values, but they do not appear at present to be commercially available for the purpose in hand.
>
> "A typical analysis for a suitable high carbon steel is as follows:

Carbon	0.60 to 0.70 per cent., both inclusive.
Manganese	0.50 to 0.80 " " "
Silicon	0.12 to 0.20 " " "
Sulphur	Not over 0.04 per cent.
Phosphorus	Not over 0.04 per cent.

> "While the refinements of manufacture of acid open hearth steel appear to insure a somewhat more uniform product, the characteristics described herewith may be obtained from higher acid or basic open hearth stock. Skill and care are necessary, however, in rolling, drawing, heat-treating and galvanizing, to produce the finished results.
>
> "The complete galvanized wire should stand the regulation sulphate of copper test. Four one-minute immersions are required for wires having a finished diameter over 0.094 inch. Three one-minute and one one-half-minute immersions for sizes 0.094 inch to 0.074 inch, inclusive. Three for sizes smaller than 0.074 inch.

"The ultimate tensile strength of the finished wire should be not less than 180,000 lb. per square inch for any size.

"The elastic limit should be not less than 130,000 lb. per square inch for any size. This point corresponds to the drop of the beam in the testing machine, and is in reality the yield point.

"While it is possible by merely hard drawing to produce these values of ultimate strength and elastic limit, the wire would be brittle unless it possessed in addition the following characteristics:

"The ultimate elongation in 8 inches should be from 4 to 5 per cent. A bend test should be made in a vise having the jaws rounded off to a 3/16 inch radius. From the vertical position to 90 degrees to the right is counted as one bend. From the latter position to the vertical is counted as two. A bend 90 degrees to the left is counted as three, and so on alternately until fracture occurs. Wires 0.188 inch in diameter should stand at least four bends, and wires 0.053 inch in diameter should stand forty-one bends with intermediate sizes in approximate proportion."

Composite Cables (Theory).—When two materials of fundamentally different physical properties are associated by being stranded together in a cable, a number of interesting problems arise in regard to their behavior under operating conditions. In studying their characteristics, certain assumptions must be made to simplify the problem. In the first place, it is presumed that the straight line relation of stress to strain is representative of conditions below the elastic limit, that is within the limits of normal operation, and that this relation is truly represented by the constant E, the modulus of elasticity for either material. Secondly whilst it is not permissible for the stress to exceed the limit of proportionality, it is equally necessary that it shall not at any time approximate to zero in either of the components. With these concessions it is possible to show that the composite

cable behaves in the same way as an elastic material, the characteristics of which are a compromise of those of the components.

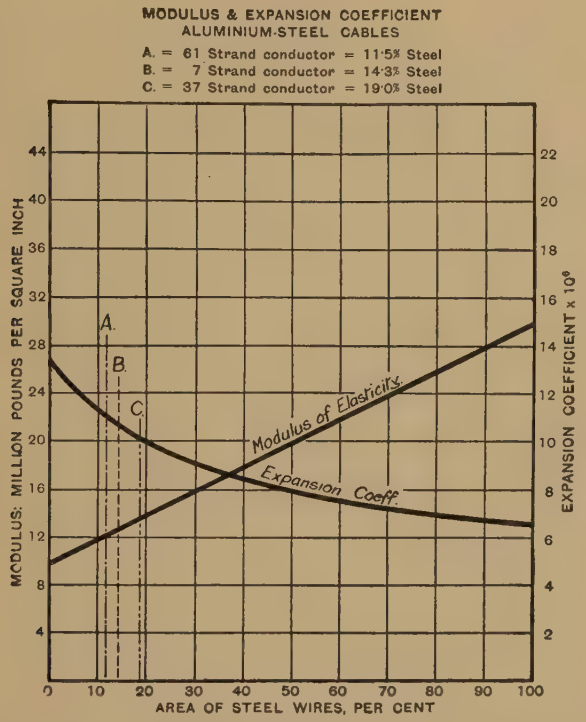


FIG. 9.—Properties of aluminum-steel conductors with different proportions of steel area.

When composite cables were first analyzed, the possibility of slip between the wires of high and low elastic extension was thought to be significant. Since that time the actual operating experience of more than twelve years has shown that slip does not take place. As a matter of practical knowledge it will be admitted that even with a reasonably short length of stranded cable it is impossible to pull out the core without breaking the wire. The friction which operates to bind the wires intimately together is equally manifest in a cable of aluminum and steel, and is still more so when there is a tension on the cable. This

tension in the helix has a centripetal component clamping the envelope down on the cores.

Under any given tension therefore the tendency of the aluminum to extend at a greater rate than the steel is restrained by the friction of the two. Then the tendency to extend is manifest in the form of a stress. The greater specific extension of the aluminum increases the tension in the steel, and the lower extension of the steel induces a compression on the aluminum which reduces its tensile stress. In this way it will be seen that the composite conductor tends to possess a modulus of its own, and it may be added, a temperature expansion coefficient of its own also.

For the individual wires and for the cable, the fundamental properties are as follows:

Modulus of elasticity for aluminum, E_a; for steel, E_s; for cable, E.

Coefficient of expansion for aluminum, a_a; for steel, a_s; for cable, a.

Area, per cent. of total, for aluminum, A_a; for steel, A_s; for cable, A.

Then the modulus of elasticity E for the composite cable is made up of two factors—

$$E = E_s \times A_s + E_a \times A_a \qquad (1)$$

for a thirty-seven strand cable of standard form the values would be

$$\begin{aligned} E_a &= 9 \times 10^6 \\ E_s &= 30 \times 10^6 \\ A_a &= 81 \text{ per cent.} \\ A_s &= 19 \text{ per cent.} \\ E &= \left[\frac{30 \times 19}{100} + \frac{9 \times 81}{100}\right] \times 10^6 \\ &= [5.7 + 7.3] \times 10^6 \\ &= 13 \times 10^6 \end{aligned}$$

For different types of stranding the value of E will vary be-

tween the limits of nine million and 30 million. In a similar way, the value of the expansion coefficient can be arrived at.

Considering a thirty-seven strand cable of the usual proportions of thirty wires of aluminum and seven of steel—

$$\alpha = \frac{E_a \times A_a}{E}\alpha_a, \quad \frac{E_s \times A_s}{E}\alpha_s \qquad (2)$$

$$= \left[\left(\frac{9 \times 81}{13 \times 100}\right) \times 13.2 + \left(\frac{30 \times 19}{13 \times 100}\right) \times 6.4\right] \times 10^{-6}$$

$$= [7.3 + 2.8] \times 10^{-6}$$

$$= 10.10 \times 10^{-6}$$

Under stringing conditions the come-along or other type of clamp is connected to the cable in such a way that the aluminum and the steel are held solidly together and strained up in unison. Then at the moment when the cable has been clamped off at the anchor points the relation of the tensions in the two components is as follows:

W = total tension in cable in pounds.
W_a = tension in aluminum component in pounds.
W_s = tension in steel component in pounds.

$$W = W_s + W_a$$

$$\frac{W_s}{E \times A_s} = \frac{W_a}{E_a \times A_a}$$

In the case of the thirty-seven strand cable already considered—

$$W_s = 78 \text{ per cent. } W_a \qquad (3)$$

or

$$W_s = 44 \text{ per cent. } W \qquad (4)$$

The foregoing expressions, it will be seen, are merely different ways of showing the equality of expansion and contraction between the two components.

When the cable has been clamped off on the span and the load is no longer applied by means of an axial tension, automatic extension of the wires will take place with change of temperature and external load. The relation of the tension in the components is no longer constant, but varying, and although, as

already shown, the steel wires carry 44 per cent. of the tension in a thirty-seven strand cable when erected, this percentage will rise and fall with change in temperature. A necessary prelim-

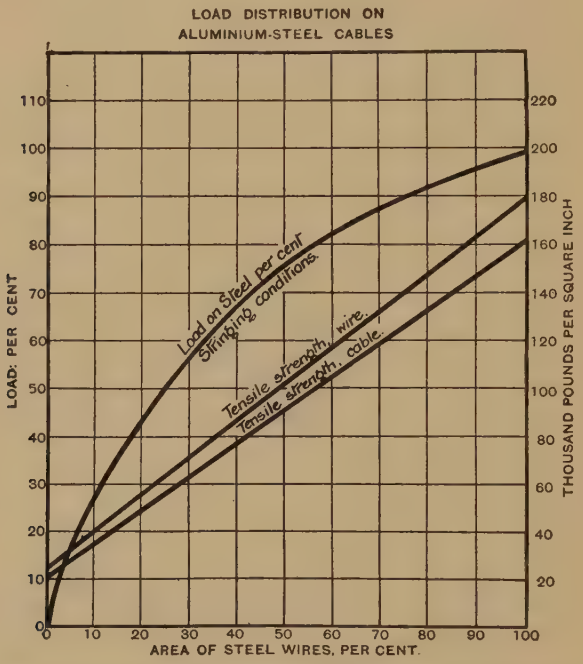


FIG. 10.—Tensile strength of aluminum-steel conductors with different proportions of steel, showing also the percentage load carried by the steel.

inary in the mechanical design of the line is to calculate the change in the sag and the total tension in the cable with varying temperature. This total tension is apportioned between the steel and the aluminum in a manner which can now be shown, and it is necessary to determine the proportions to ascertain that the aluminum will not, under severe loading conditions, be stressed beyond its elastic limit.

For a change in temperature from that at which the conductor is strung the change in length will be

$$\Delta L = \alpha t - \frac{\Delta S}{E} \qquad (5)$$

In other words, the thermal extension is partly offset by the simultaneous elastic contraction. (The above expression refers,

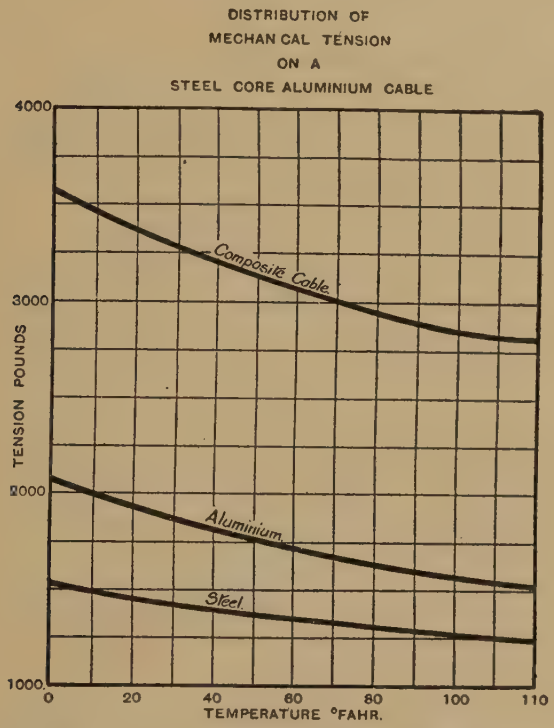


FIG. 11.—Variation of load on an aluminum-steel conductor with changing temperature.

of course, to the composite cable.) As the extension on both components is the same,

$$\alpha t - \frac{\Delta S}{E} = \alpha_a t - \frac{\Delta S_a}{E_a} \tag{6}$$

$$\Delta S_a = E_a \left[\frac{\Delta S}{E} + (\alpha_a t - \alpha t) \right] \tag{7}$$

From the tension-temperature curve for the cable it is easy to determine a series of values for temperature and a corresponding difference in tension, this difference being positive for lower tem-

peratures, and negative for higher temperatures than that of stringing. The remainder of the expression is constant, and the difference in the aluminum stress is easily found. As the normal or stringing tension of the aluminum is 56 per cent. of that in the entire cable, this figure must be used in calculating the normal stress. Obviously, the conditions will vary according to the temperature at which the line is constructed, and if it is pulled in in very cold weather a study of the above relation may show that the tension in the aluminum will disappear at maximum summer conditions. On the other hand, if strung in the height of summer it may be found that the tension in the aluminum will approach or exceed the elastic limit with minimum temperature. These conditions do not often arise, and if they do, a change in the design loadings is indicated. In the curves attached (Fig. 11) these properties of composite cables are shown graphically to better effect than in the above expressions.

It will be admitted that present knowledge of the mechanical characteristics of stranded conductors is unsatisfactory. Neither steel, aluminum nor copper wire possesses a straight line elastic curve; in other words, the value of E varies with different loading, and this naturally affects to a small degree the distribution between the components of a composite cable. Furthermore, the degree to which the helix acts as a spring in slightly winding and unwinding when under tension is unknown; this also tends to make the elastic modulus somewhat variable. In these matters present knowledge of the properties of composite cables is not inferior to that of the characteristics of a simple cable. Actual operating experience with composite cables and such experiments as are possible have indicated that fundamentally the adoption of a constant modulus and expansion coefficient for each type of cable is not unsound.

A very significant comment on the characteristics of composite cables is offered by A. E. Silver in a paper on the subject of 220-kilovolt transmission:*

* *Transactions A. I. E. E.*, vol. xxxviii, p. 1056.

"The mechanical characteristics of steel-core aluminum cables are complicated, and calculation of stresses and sags under varying loading and topographical conditions presents an involved and difficult problem. This is due to the fact that the coefficients of expansion and moduli of elasticity are different for the two metals, and consequently are not accurately determinable for the composite cables. The cable manufacturers, however, have investigated these characteristics, and have developed practical, though laborious, methods of calculation of conductor stresses and sags. These methods have been followed, and are considered in the main to give results of an accuracy satisfactory for design purposes.

"The basic data for calculations have been taken as:

	Aluminum.	Steel.
Elastic limit (lb. sq. in.)	14,000	130,000
Modulus of elasticity (lb. sq. in.)	9×10^6	30×10^6
Coefficient of expansion (per degree F.)	12.8×10^{-6}	6.4×10^{-6}
Elastic limit of composite cable, 17,300 lb. (716,000 cir. mils aluminum, 93,000 cir. mils steel).		

"Within any limits thus far investigated, it appears economical, under the design loading, to utilize the full strength of the conductor up to its elastic limit, *i.e.*, to keep sags to a minimum, this enabling use of shorter towers or longer spans at the expense of stronger supporting structures at angles and dead-end points. With a new aluminum-steel cable, when the loading has been reached which will stress the steel core to its elastic limit, the aluminum will have passed its elastic limit and in consequence have been permanently stretched. The full working strength of the cable, 17,300 lb., will then have been developed, and it may then be said to have reached its final stretched condition, *i.e.*, to have received its 'permanent set.' As the heavy design loading is removed, the action of the aluminum strands will be to loosen infinitesimally

on the steel core and to take no stress. In any subsequent applications of the design loading, the core will again be stressed to the elastic limit of the steel, and the aluminum will coincidentally reach its own elastic limit stress. At lighter loadings the aluminum will be a dead load upon the steel core, which will carry all of the stress.

ALUMINUM-STEEL CONDUCTOR.

No. of Aluminum wires	30 × 0.116 ins.
No. of Steel wires	7 × 0.116 ins.
Area of Aluminum	0.321 sq. ins.
Elastic limit	11,400 lbs. sq. ins.
Modulus of Elasticity	9.8×10^6

"This introduces an interesting feature, in that the characteristics of the composite cable when new are dis-

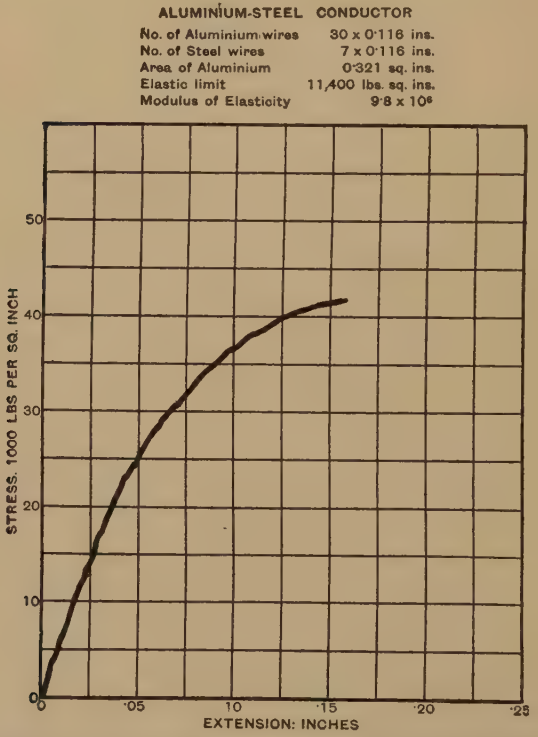


FIG. 12.—Autographic stress-extension curve for an aluminum-steel conductor.

tinctly different from its characteristics after it has received its 'permanent set,' and for loadings less than the design loading, will follow different tension-sag curves.

"The problem of predetermining stringing sags for a suspension insulator line, in which there will be considerable differences in lengths of adjoining spans and in elevations of the ends of individual spans, involves considerations of unbalanced tower loads, abnormal insulator loads, and reduced tower and ground clearances under varying conditions of conductor loading. It is necessary, initially, to assume a somewhat different mental attitude toward the problem of conductor stringing than that which largely has been customary. For the conditions of 220-kv. design, with heavy design loadings and large conductors under heavy tension, the problem assumes greater importance in transmission line practice than heretofore. In usual practice on suspension insulator lines, the conductor is strung to a certain predetermined tension, derived from tension-sag curves on the basis of the average span length between dead-end points, and the suspension insulators are then tied in a vertical position. It is assumed that when the design loadings occur, the conductor tensions and attendant loads upon insulators and towers will continue to maintain the condition of proper balance of stresses within reasonably close limits. Probably, with most present lines, the resulting unbalanced effects under design loading will not be serious. Under the assumed 220-kv. design conditions, preliminary study has shown that such a method of stringing will result, under the extremely heavy design loading, in great longitudinal deflections of suspension insulators intended to operate purely as suspension units, and will consequently impose unsafe tensions upon these insulators, with attendant unbalancing of tower loads and possibly dangerous reduction in tower clearances, in addition to over-stressing and stretching the conductor itself."

Composite Cables (Practice).—In operating practice, using conductors of simple aluminum, it has sometimes been found necessary after two or three years' service to restring the line throughout, due to the permanent increase in sag having reduced the clearance. From a study of the actual mechanical load, however, it would not appear that the primitive yield point had been exceeded, and the only inference was that with a steady load of less than half the ultimate strength, a slight but cumulative permanent set would be experienced. In this effect the time element is of importance, and the extension would seem to follow a logarithmic law. Tests have shown that with a long-period test of several months the wire will break under a load only 80 per cent. of its rated ultimate strength. Lesser loads than this will yield a permanent set, as already shown, but after a given time extension will cease. Although aluminum wire is used as an illustration, the same is true to a greater or lesser extent of any hard-drawn wire with the possible exception of steel. The fact may be expressed by saying that the load extension curve is always slightly concave, or that the modulus tends to diminish with increasing load. An inspection of test curves will confirm this. Careful manufacture, however, will reduce this effect, but never quite eliminate it. On the other hand, hard-drawn steel wire, properly manufactured, will yield an elastic curve which is nearly perfect, the limits being clearly defined. Obviously then the combination of aluminum and steel is particularly appropriate, because, at the first indication of a departure from straight line extension of the aluminum, the steel will take up the load and the differential effect will hold down the extension of the envelope at the expense of slightly greater stress in the core.

It is sometimes questioned whether the full strength of all the components will be developed before the cable breaks. Strictly, this can be true if the ultimate elongation of the aluminum wires is equal to that of the steel. In actual fact, they elongate only about one half as much, and in consequence of this the envelope must break first, although a very considerable load is simul-

taneously carried by the core. This load is instantaneously increased by the amount thrown off the aluminum, and in a testing machine the steel will next elongate and break, although

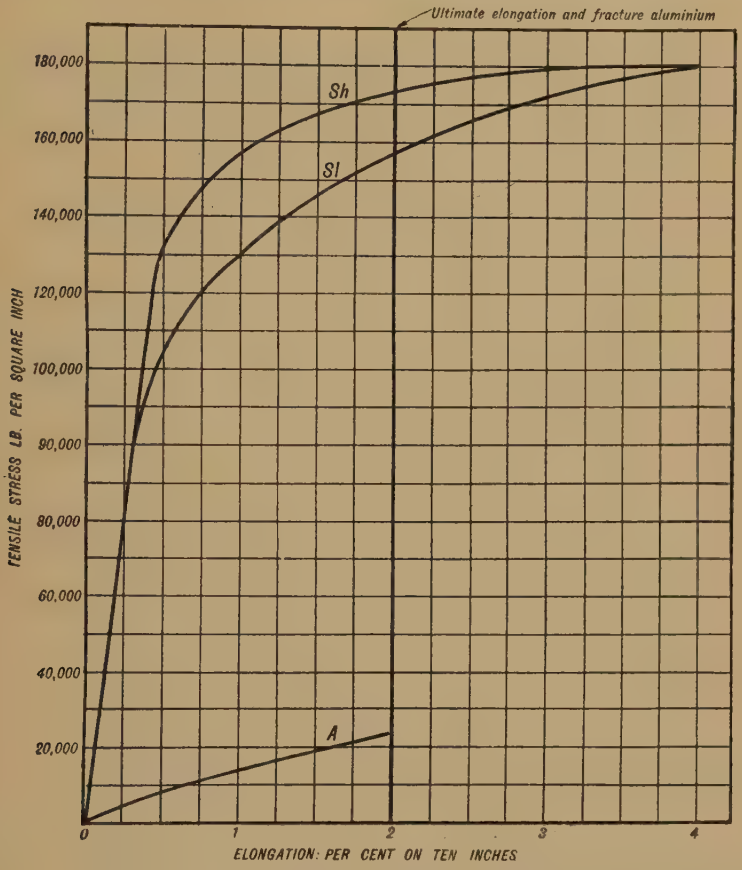


FIG. 13.—Characteristics of aluminum wire (A) compared with steel of high and low elastic limits (Sh and Sl) respectively. According to the quality of the steel wire, 96 per cent. or 86 per cent. of its total strength is developed before fracture.

on the line this extra elongation would relieve the load and probably the wires would not come down. It will be seen by reference to figure 13 that the entire strength of the aluminum wires will be developed, in addition to that proportion of the

strength of the steel which is loaded when the aluminum fails. This may be from 80 to 95 per cent. of the total strength of the core and depends upon two factors: (*a*) the ratio of ultimate elongation between the envelope and the core, and (*b*) the shape of the load extension curve of the steel wire. For a cable of good characteristics the aluminum elongation should be as high as possible and the steel should have a high elastic limit.

The following figures exemplify the steel-cored aluminum cable in present use:

TABLE 5.—*Properties of Aluminum and Steel.*

	Aluminum.	Steel.
Tensile strength (lb. sq. in.)	25,000	180,000
Proportional limit	14,000	130,000
Modulus of elasticity	9×10^6	30×10^6
Elongation per cent. on 10 in.	2	4
Expansion per degree F.	13.2×10^{-6}	6.4×10^{-6}

Some of the above figures may vary, according to the size and quality of the wire; furthermore, the elastic limit of the aluminum is not sufficiently definite to connote a fundamental property. The figure quoted represents the maximum stress at which no appreciable permanent set is registered after the load is held for one minute. Steel wire is always double galvanized and may be obtained with tensile strength 25 per cent. higher than the above figure. Such wire is of limited applications, however, and is exceedingly stiff. Using wire of the above quality, the characteristics of the finished composite cable will be as follows:

TABLE 6.—*Properties of Aluminum-Steel Cables.*

Maximum size (cir. mils.)	83,000	126,000	600,000	1,260,000
" " (sq. in.)	0.066	0.100	0.500	1.00
Strands aluminum	6	6	30	54
Strands steel	1	7	7	7
Ratio of steel (per cent.)	14.3	13.0	18.9	13.0
Ultimate strength (lb. sq. in.)	43,500	40,600	49,000	40,600
Modulus of elasticity	12.0×10^6	11.7×10^6	13.0×10^6	11.7×10^6
Expansion per degree F.	10.8×10^{-6}	10.9×10^{-6}	10.1×10^{-6}	10.9×10^{-6}

The ultimate strength shown in the above tables is assumed at 90 per cent. of the summated strength of the wires, but this is purely a convention, and, as already shown, the shape of the test curves may modify the figure. These quantities are by no means standard, because at the moment of writing no standards on composite cables have been published in the U. S., nevertheless many hundreds of miles of wire have been strung with the above properties.

It has been noted that some disadvantage attaches to the conventional 37 strand aluminum-steel conductor because of the high percentage of steel figured on the total cross section. In order to utilize such a conductor economically it is not possible to take full advantage of the steel reinforcement, because in such a case the mechanical tension becomes undesirably high for the supporting structures. As a compromise therefore an alternative type of conductor is being used embodying a core of seven steel wires surrounded by an envelope of twenty-six aluminum wires in two layers. To satisfy this combination it will be seen that the aluminum wires should individually be 35 per cent. greater in diameter than the steel. The ratio of steel to total cross section is 13 per cent.

A study of the practical aspects of the use of aluminum-steel cables was made under the direction of the British Electrical and Allied Industries Research Association, and published in 1923 (*Journal I. E. E.*, vol. 61, No. 332, p. 1041). The conclusions arrived at after a long series of tests, at the National Physical Laboratory at Teddington, were to the effect that the properties of a composite cable can be reasonably well predetermined by simple arithmetic. Limit of proportionality is not clearly defined originally, but tends to center at 60 per cent. of the ultimate strength after repeated loading, which eliminates the preliminary stretch of any stranded conductor. What is far more significant is the fact that this load was maintained at the approximate proportional limit for eight days without resulting in any abnormal effect on the cable, demonstrating positively the rational basis for a safety factor of not more than

two in stringing the cable. While it is recommended that steel-cored cable should be strung by first stretching up to the proportional limit and then reducing the load, this is only practicable with very small conductors and generally cannot be adopted in the field.

One of the most important contributions to the study of composite cables was made in Germany by cooperation between the Government Testing Laboratories at Dahlem and three principal electrical manufacturers, namely the Allgemeine Elektrizitats Gesellschaft, the Felten Guilleaume Carlswerk and the Siemens Schuckertwerk. In these experiments which were very fully reported by Dr. A. Burklin (*Elektrotechnische Zeitschrift,* Oct. 23, 1924) three groups of determination were made as follows:

(*a*) Tensile and elastic constants both for aluminum-steel and the equivalent copper conductors.
(*b*) Corresponding values for the individual component wires.
(*c*) Temperature expansion coefficients for aluminum-steel and the equivalent copper cable.

Experiments (*a*) and (*b*) were made in the State Laboratory on samples seven to ten feet in length while the temperature expansion coefficients and the elastic modulus were determined on a span of 328 feet horizontally suspended under cover with temperature control and the necessary gauges and instruments. The series of composite conductors used in the tests varied from 120,000 circular mils (0.94 sq. in.) up to 400,000 cir. mils (0.32 sq. in.) aluminum area. A uniform stranding was used throughout this range of sizes and consisted of seven strands of steel for the core surrounded by two layers of aluminum of ten and sixteen wires respectively. Allowing for the respective sizes of the wires the percentage of total area occupied by the steel was approximately 14 to 15 and the resulting cable would therefore have similar characteristics to the more usual combination of six aluminum and one steel wire all of equal diameter.

The stranding used for these experiments however had the merit that it was practicable to use it over a very wide range of sizes and so derive a consistent series of results. For commercial use such a method of stranding would cost a little more to produce than the designs now common in this country but even so it would have much practical advantage. Both on account of physical properties and ease of handling the desirable size of aluminum wire is somewhat larger than that of steel wire notwithstanding which it is customary in America to strand up composite conductors having all wires of the same diameter. In the cables covered by these tests it will be seen that the aluminum strands are from twenty to twenty-five per cent. larger than the steel and other things being equal this is distinctly good practice.

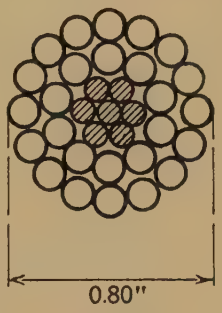


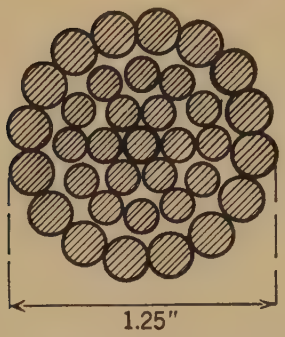
FIG. 14.—Special aluminum-steel stranding (see Table 7).

In the following table the results of the experiments are very briefly summarized:

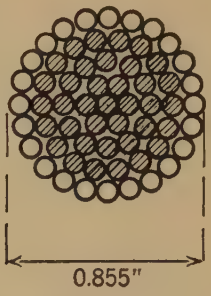
TABLE 7.—*Properties of Aluminum-Steel Conductors (as determined by A. Burklin).*

Conductor size, cir. mils....	124,000	178,000	256,000	328,000	414,000
Stranding, aluminum.....	26×0.069	26×0.083	26×0.099	26×0.112	26×0.126
" steel.....	7×0.058	7×0.065	7×0.080	7×0.089	7×0.098
Steel area, per cent.....	16	14.5	14.8	14.5	14
Tensile strength, lb. sq. in.					
Steel.....	197,000	213,000	171,000	184,000	210,000
Cable.....	49,800	46,300	—	45,600	47,000
Tensile ratio, cable/wire, per cent.....	90	82.5	—	92.2	84.9
Modulus of elasticity (on long span).....	10^6×10.65	—	10.30	—	10.90
Expansion coefficient ° F. (on long span).....	10^{-6}×10.60	—	10.65	—	10.70

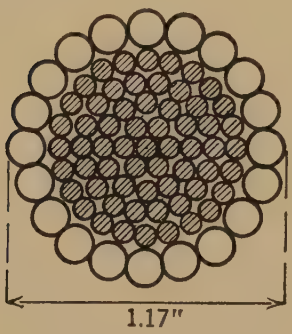
The foregoing tests as well as those made by the British authorities already quoted, confirm the calculated constants for aluminum-steel conductors with remarkable fidelity. In practical use therefore it is reasonably safe to say that the behavior



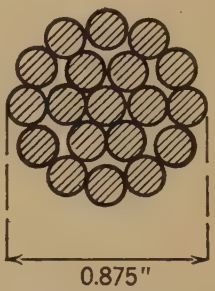
Narrows Crossing, Tacoma; 6241 feet, steel cable, 35 strand.



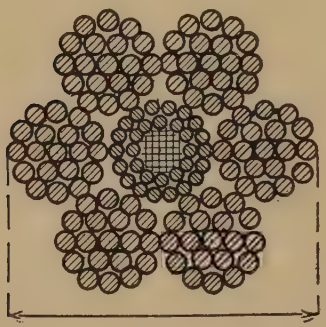
Great Western Power Co.; 4753 feet, aluminum-steel, 24 + 37 strand.



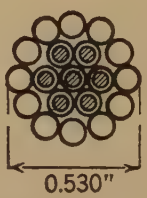
Knoxville Power Co.; 5010 feet, aluminum-steel, 22 + 61 strand.



Pacific Gas & Electric Co.; 4427 feet, steel cable, 19 strand.



Shawinigan Water & Power Co.; 4801 feet, steel cable, rope strand.



W. Virginia-Maryland Power Co.; 4317 feet, copper, copper-clad cable.

FIG. 15.—Special conductors for long spans.

of these composite cables will agree with arithmetical laws already outlined. In surveying the experiments of this German investigation it will be noted that no determinations have been made of the yield point or of the ultimate elongation of the conductors. Further research is therefore called for in these directions before the available empirical data can be regarded as complete.

In any calculations of the extension or elongation of composite cables, it will be found that a very small change in length may effect a most important change in the stress distribution. Considering the equation No. 7 on p. 29, it may be found that under the most heavy loading, in some circumstances the aluminum will take too great a share of the load. The distribution may, however, be entirely changed by a modification of the stranding operation, and it has been suggested to place the core under mechanical strain as it feeds into the strander. This requires a brake and dynamometer and tensioning device, and is not entirely practical. It is, however, possible to put an initial extension on the steel by mounting the core drum in a small electrically heated oven with thermostatic control, thus feeding a hot wire in as a core and stranding around it a cold envelope. Allowance would be made for thermal losses, but the net result would be a core under an initial strain, so that with zero stress in the envelope there would be a positive tension on the middle wires. For certain conditions this type of conductor would be useful.

Reference has already been made to the somewhat indefinite elongation pertaining to any stranded cable, but the effect of the stranding pitch on this quantity has not been discussed. Ordinarily, a cable is stranded so that the steel wires have a pitch ratio of twenty to thirty, and the outer envelope from fifteen to twenty-five. If the envelope is laid with a much shorter pitch than the core, the latter will tend to take a greater proportion of the load, and practically the aluminum wires will become simply part of that load. This fact is useful in the production of cable for use as a messenger for catenary trolley wire sus-

pension; obviously it is essential to reduce to a minimum the changes in length due to temperature. By the means indicated, the steel will dictate the extension and contraction of the wire, which will therefore be limited by reason of the low expansion coefficient. It is fair to argue that in this type of cable the envelope will not take its due proportion of the load. However, this is not significant, because the character of the installation is such that the steel wire is sufficient to carry the entire tension.

Other modifications in the practical use of aluminum-steel cable arise when exceptionally long spans must be strung. In such an installation the regular method of stranding is not entirely adequate. The tension on such a crossing may often exceed 20,000 lb. to maintain the requisite clearance limits and a much larger proportion of steel is thereby necessitated. No difficulty arises, however, because with the standard symmetrical concentric stranding any number of layers may constitute the core and envelope respectively. While this study has referred more specifically to aluminum cable with a steel core, it is clear that the composite conductor theory is entirely practicable for other combinations, such as copper with a copper-clad, phosphor-bronze or silicon-bronze core, and such combinations may soon be seen in commercial use. Copper cables with a galvanized steel core have been employed, but with serious results arising from the rapid decay of the zinc, and it has been found necessary in such a cable to tin the wires of the envelope, thus avoiding contact electrolysis. The Utah Power and Light Co. has a very extensive mileage of such composite copper-steel wire in use on their 130-kilovolt lines, and the Mississippi River Power Co. also employs a steel core copper cable for one of their long crossings of the Missouri River.

The most significant merit possessed by aluminum-steel as compared with such combinations as copper-steel, copper-bronze and other forms of composite conductor is that due to the considerable disparity between the elastic moduli of the two components. This fact has not been sufficiently emphasized in studies of composite cables and it is thought worthy of particu-

lar reference here. Aluminum has a modulus of approximately one third while copper has a modulus of about two thirds that of steel. Since the tension of the component wires within the elastic range is proportional to their respective moduli it is clear that in the aluminum-steel cable the steel core will take up a more important share of the load than it will in the case of the copper-steel combination and in the case of a copper cable reinforced by a bronze core the difference of elasticity existing between the two materials is not sufficient to load the core wires effectively with increasing external loads notwithstanding their intrinsically high tensile strength. For a composite cable to function effectively under changing load conditions it is fundamentally important that the core shall possess not only a high tensile strength as compared with the envelope but that it shall also have an inherently higher elastic modulus.

TABLE 8.—*Physical Properties of Conductor Wires.*

Material.	Copper.	Aluminum.	Bronze.
Density	8.89	2.70	8.89
Conductivity (per cent.)	98	60	65
Tensile strength (lb. sq. in.)	55,000	25,000	70,000
Modulus of elasticity	18×10^6	9×10^6	19×10^6
Expansion coefficient (per degree F.)	9.5×10^{-6}	13.2×10^{-6}	9.4×10^{-6}
Ultimate elongation on 10 in. (per cent.)	1	2	3
Melting point (degrees F.)	2,012	1,215	—
Tensile strength : weight ratio	1.00	1.50	1.30
Weight per 1,000 ft. per 1 sq. in. (lb.)	3,850	1,170	3,850
Weight per 1,000 ft. per ohm (lb.)	172	87.5	260

Material.	Copper-clad.	Aluminum alloy.	Steel.
Density	8.18	2.80	7.85
Conductivity (per cent.)	39	50	8.7
Tensile strength (lb. sq. in.)	100,000	40,000	75,000
Modulus of elasticity	20×10^6	—	30×10^6
Expansion coefficient (per degree F.)	7.2×10^{-6}	—	6.4×10^{-6}
Ultimate elongation on 10 in. (per cent.)	1	1	5
Melting point (degrees F.)	2,012	1,150	2,480
Tensile strength : weight ratio	1.96	2.30	1.54
Weight per 1,000 ft. per 1 sq. in. (lb.)	3,550	1,220	3,400
Weight per 1,000 ft. per ohm (lb.)	399	107	1,710

In the above table the quantities relate to single hard-drawn

wires of 0.100 to 0.120 inch diameter. Bronze and steel are not of the high tensile reinforcing grade, but are of somewhat lower strength and high conductivity.

The foregoing comments on composite cable practice relate almost entirely to the methods followed in America. Several types of composite conductors have been produced in Germany, where the practice is somewhat different. Some of the earliest investigators contended that in an aluminum-steel conductor the steel should form the envelope and the aluminum the core. Later, in adopting the central steel core, it was supposed that the elastic extension of the core should be inadequate, and a hemp center was used, surrounded by a tightly wound spiral of steel. This expedient was of course discovered to be unnecessary. The most recent practice is more conventional, except that in place of a steel core amounting to from 13 to 20 per cent., the gross area, German mills have been producing cable having 20 to 33 per cent. steel. In the case of the high-tension lines from Spremberg to Berlin, the cables have an area of 0.236 square inch aluminum, and 0.078 square inch steel, a ratio of 25 per cent. Ultimate strength of the wires is 27,000 and 170,000 lb. per square inch respectively, the entire conductor having an ultimate tension of nearly 57,000 lb. per square inch. Under the most severe loading, however, it has been customary to estimate upon the strength of the steel alone, and

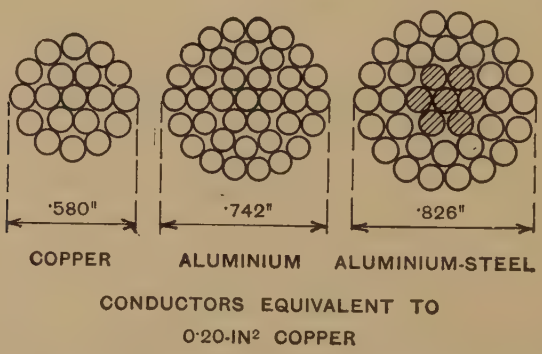


FIG. 16.—Relative sectional areas of copper, aluminum and aluminum-steel conductors of the same conductance.

German engineers until recently did not endorse the presumption that with increased loading the aluminum assumes a greater share of the total load on the cable.

Selection of Conductors.—A study of the constants presented in the foregoing table will show that as a transmission line conductor no material need be seriously considered other than copper, aluminum or aluminum-steel. Aluminum alloy wire appears to be worth study, but at present it is almost entirely undeveloped. Steel, bronze and copper-clad wire are valuable in a distinctly important field of construction, that of long harbor or river crossings, where conductivity is of less importance than the tenacity: weight ratio, but in long-distance line construction the contrary is true.

To make an instructive illustration, an installation will be assumed of a 150-kilovolt double circuit transmission line having a maximum load capacity of 50,000 kw. per circuit at 60 cycles, and a length of from 100 to 200 miles. Assuming that synchronous machinery would be used in the receiving station, conductor wires equivalent to 255,000 cir. mils (0.20 square inch) copper would be employed. In the following table details of three comparative conductors are set out:

TABLE 9.—*Comparison of Conductors for 150-kilovolt Transmission Line.*

Material.	Copper.	Aluminum.	Aluminum-steel.
Area (cir. mils)	255,000	415,000	(415,000)
Area (sq. in.)	0.200	0.327	(0.327)
Strands	7 or 37	37	30 + 7
Diameter of strands (in.)	0.193 or 0.083	0.106	0.118
Diameter of cable (in.)	0.581	0.742	0.826
Weight per foot (lb.)	0.780	0.390	0.656

In following this comparison further it may be necessary to take account of loading on the wire and assume first that under winter conditions a coating of ice ½ inch thick will load the wires in addition to a horizontal wind load equivalent to 8 lb. per square foot on the projected surface of the wire. These conditions coincide with the heavy loading conditions of the

National Electric Safety Code, and also form the design assumptions for probably the major part of the construction in the United States. On these assumptions it is possible to derive the total load on the wire and the tension.

Table 10 is intended simply as an illustration of comparative figures only and does not purport to outline the best design constants for all conditions. For example, the working stress has been assumed at 40 per cent. of the ultimate load; this is simply a matter of judgment, in some conditions 50 per cent., and in others 30 per cent. might be more economical.

TABLE 10.—*Loading Conditions for Conductors on 150-kilovolt Transmission Line.*

	Copper.	Aluminum.	Aluminum-steel.
Area (cir. mils)	255,000	415,000	(415,000)
Area (sq. in.)	0.200	0.327	(0.327)
Diameter (in.)	0.581	0.742	0.826
Diameter with ½-in. ice coating (in.)	1.581	1.742	1.826
Weight of conductor w (lb.)	0.780	0.390	0.656
Weight of ½-in. ice coating (lb.)	0.665	0.775	0.836
Total weight W (lb.)	1.440	1.165	1.492
Wind load per foot P (lb.)	1.050	1.160	1.224
Total resultant load $R = \sqrt{W^2 + P^2}$	1.790	1.640	1.930
Ratio R/w	2.300	4.210	2.940
Ultimate stress (lb. sq. in.)	54,000	25,000	52,000
Maximum working stress (lb.)	21,600	10,000	20,800
Maximum tension	4,320	3,270	8,400

Briefly, estimating the maximum sag for the copper conductors at a summer temperature of 100° F., it is found to be about 25 feet for a span of 750 feet between supports. If this sag be adopted for all the conductors, a uniform height of support can be used and the spans become as shown below.

TABLE 11.—*Sags and Span Lengths for the 150-kilovolt Transmission Line.*

	Copper.	Aluminum.	Aluminum-steel.
Maximum sag at 100° F. (ft.)	25	25	25
Average span on level (ft.)	750	650	1,000
Towers per mile	7.5	8.1	5.5
Ground clearance	25	25	25
Height of towers:			
(*a*) To lower crossarm (ft.)	55	55	55
(*b*) To apex (ft.)	85	85	85

Although this study is only quite superficial, it is sufficient to illustrate the method by which different conductors may be compared. Obviously, local conditions will modify the whole complexion of the design. If, for instance, no ice loading need be allowed for, then the permissible span for aluminum wire will be increased, and this conductor will show a much better case. In mountainous country much longer spans are usual, and here the conductor with the highest tenacity: weight ratio will afford the best engineering.

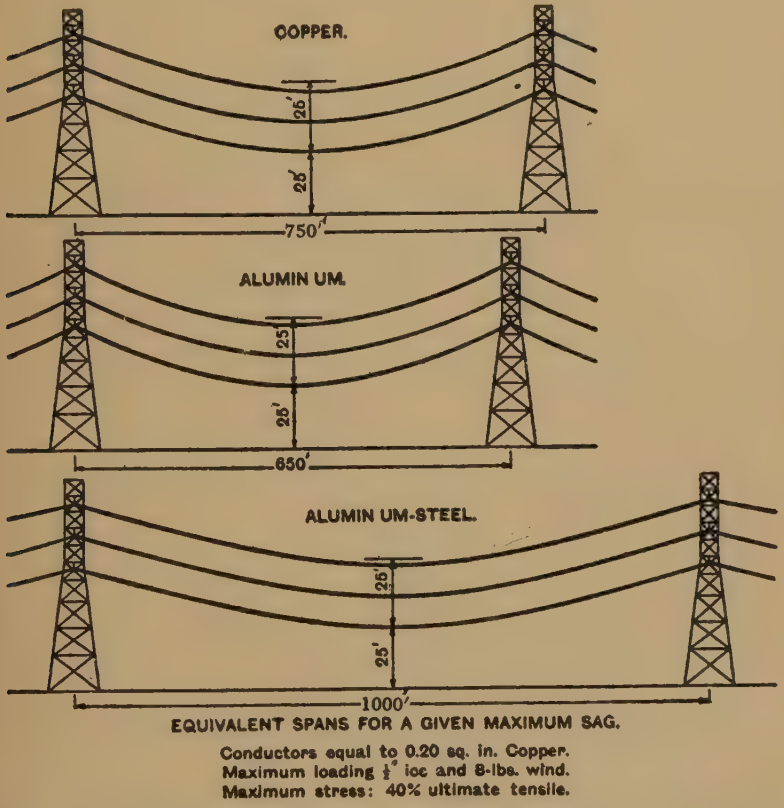


FIG. 17.—Appropriate span lengths for three types of conductor of equivalent size.

It has been mentioned that occasions arise where the resistance of the conductor is not the most significant element in

the design. Where the voltage is more than 154 kilovolts or where the altitude of the line is high and the climate stormy, the phenomenon of corona will be manifested and a continuous discharge of energy will take place from the conductor wires. The critical voltage at which discharge begins can be raised by an increase in the diameter of the wire. In this way a factor is introduced which at once modifies the conductor design. If it requires a wire of 0.25 square inch to transmit 50,000 kva. at 110 kilovolts, then with double the voltage and the same current density a wire of 0.125 square inch would be sufficient. But such a conductor would be subject to a very low critical voltage and a consequently high corona loss. It is, therefore, necessary to employ a wire considerably larger than is required for considerations of voltage drop, but since only the diameter is significant, it is possible to use a composite or artificially enlarged cable. Such combinations as steel-cored aluminum, steel-cored copper, hollow-core copper, etc., have all been adopted with advantage and a comparison is set out in the following table, in which it is supposed that the minimum practicable diameter of conductor is to be 1 inch.

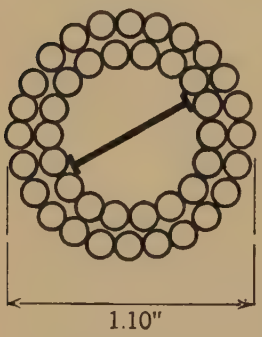


FIG. 18.—Modern form of hollow-core conductor.

In the accompanying figure the hollow-core copper conductor will be noted. This is designed to have an artificially increased diameter over a solidly stranded cable in order that losses when operating at high voltage will be minimized. In the example illustrated the core consists of a flexible tube of copper over which the conducting layers are stranded. It is obvious that the flexible tube contributes nothing to the tensile strength of the cable.

More recent modification employs an " I " section for the core, this section being given a twist and a perfectly substantial stranded conductor is the result without any tendency to collapse. With the extension of transmission systems operating

at 220 Kv. it is probable that wide use may be made of some form of conductor having an artificially increased diameter.

TABLE 12.—*Characteristics of a Series of Composite Conductors.* (See Fig. 19.)

	Steel-core aluminum.	Steel-core copper.	Copper-clad core copper.
Number of strands:			
Envelope	54	54	54
Core	7	7	7
Diameter of strand (in.)	0.111	0.111	0.111
Weight per 1,000 ft.:			
Envelope (lb.)	631	2,070	2,070
Core (lb.)	266	266	246
Total (lb.)	897	2,336	2,316
Ohms per 1,000 ft.	0.0256*	0.0154*	0.0154*
Tensile strength:			
Envelope (lb. sq. in.)	25,000	55,000	55,000
Core (lb. sq. in.)	180,000	180,000	140,000
Total (lb. sq. in.)	42,900	68,900	64,600
Ultimate tension, cable (lb.)	25,400	40,600	38,200

	Bronze-core copper.	Hollow-core copper.	Hemp-core copper.
Number of strands:			
Envelope	54	42	54
Core	7	1 (spiral)	—
Diameter of strand (in.)	0.111	0.111	0.111
Weight per 1,000 ft.:			
Envelope (lb.)	2,070	1,610	2,070
Core (lb.)	269	520	3
Total (lb.)	2,339	2,130	2,073
Ohms per 1,000 ft.	0.0154*	0.0154*	0.0154*
Tensile strength:			
Envelope (lb. sq. in.)	55,000	55,000	55,000
Core (lb. sq. in.)	125,000	—	—
Total (lb. sq. in.)	62,900	38,000	49,000
Ultimate tension, cable (lb.)	37,100	21,400	28,900

Wire Specifications.—Wherever a national standard exists it usually provides the best basis for the testing and purchase of engineering material.

The American Society for Testing Materials have issued standards on medium- and hard-drawn copper wire, as well as upon stranded copper, and the standards form the basis of commercial specifications in several foreign markets as well as in the

* Resistance neglecting core.

United States and Canada. The following is extracted from the A.S.T.M. standard for hard-drawn copper:

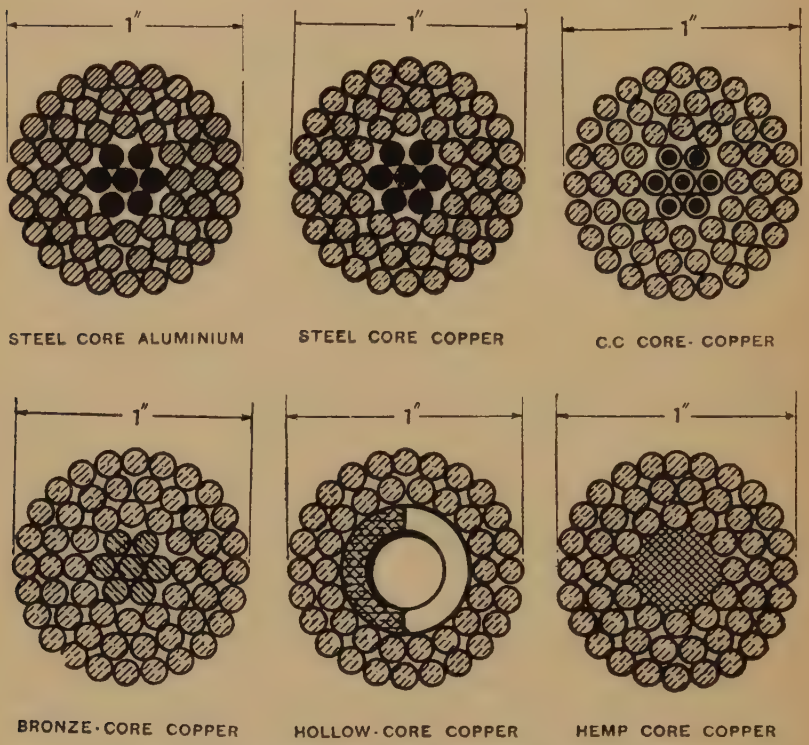


FIG. 19.—A series of alternative composite conductors designed with a diameter of 1 inch (see Table 12).

Hard-drawn Round Wire.—(*a*) Size shall be expressed as the diameter of the wire in decimal fractions of an inch, using not more than three places of decimals; that is, in mils.

(*b*) Wire is expected to be accurate in diameter; permissible variations from nominal diameter shall be—

For wire 0.100 inch in diameter and larger, 1 per cent. over or under;

For wire less than 0.100 inch in diameter, 1 mil over or under.

TABLE 13.—*Particulars of Conductors in Use on Some Important Systems.*

System.	Kilovolts.	Line.	Miles.	Circuits.	Conductors.						
					Material.	Size, cir. mils (conductor).	Size, sq. in. (conductor).	Stranding.	Ultimate tension, lbs.	Weight, lbs. per mile.	Kva. per circuit.
1. Southern California Edison Co.	220	Big Creek–Eagle Rock	241	2	Aluminum-steel	605,000	0.475	54+7	21,270	4,118	100,000
1A. Southern California Edison Co.	220	Eagle Rock–Laguna Bell	27	2	Aluminum-steel	666,000	0.524	54+7	23,500	4,550	100,000
2. Pacific Gas and Electric	220	Pit River–Cottonwood	26	2	Aluminum-steel	518,000	0.406	42+19	67,000	5,900	120,000
2A. Pacific Gas and Electric	220	Cottonwood–Vacaville	176	2	Copper	500,000	0.392	7×7	21,600	8,120	120,000
3. Great Western Power	165	Caribou–Oakland	186	1	Aluminum-steel	336,000	0.264	30+7	16,200	2,788	60,000
3A. Great Western Power	110	Feather River–Oakland	—	2	Copper	168,000	0.132	7	7,260	2,760	32,000
4. City of Seattle	165	Skagit River–Seattle	105	1	Aluminum-steel	477,000	0.375	30+7	22,700	3,920	90,000
5. Knoxville Power Co.	154	Cheoah–Marysville	27	2	Aluminum-steel	500,000	0.392	30+7	23,750	4,102	38,000
6. West Penn Power Co.	132	Windsor-Washington, etc.	160	2	Copper	211,600	0.166	19	9,140	3,480	30,000
7. Hydro-Electric Commission, Ontario	110	Niagara Falls–Toronto	80	2	Aluminum-steel	605,000	0.475	54+7	21,270	4,118	50,000
8. Victoria Electric Commission	132	Morwell–Melbourne	112	2	Aluminum-steel	336,000	0.264	30+7	16,200	2,788	25,000
9. Compania Chilena	110	Limache–Santiago	67	2	Aluminum-steel	167,800	0.132	6+1	6,660	1,227	12,500
10. Mexican Northern Power	110	Boquilla–Parral	157	2	Aluminum	211,600	0.166	7	5,100	1,400	11,250
11. Inawashiro Co., Japan	145	Inawashiro–Tokyo	140	2	Copper	198,000	0.155	19	8,500	3,240	22,000
12. Societa Interregionale, Italy	130	Brugherio–Reggio	95	1	Copper	215,000	0.169	19	9,300	3,540	40,000

(*c*) Each coil is to be gauged at three places, one near each end, and one approximately at the middle; the coil may be rejected if, two points being within the accepted limits, the third point is off gauge more than 2 per cent.; in the case of wire 0.064 inch in diameter and larger, or more than 3 per cent. in the case of wire less than 0.064 inch in diameter.

Wire shall be so drawn that its tensile strength and elongation shall be at least equal to the value stated in Table 14. Tensile tests shall be made upon fair samples, and the elongation of wire larger in diameter than 0.204 inch shall be determined as the permanent increase in length, due to the breaking of the wire in tension, measured between bench marks placed upon the wire originally 10 inches apart. The elongation of wire 0.204 inch in diameter and smaller shall be determined by measurements made between the jaws of the testing machine. The zero length shall be the distance between the jaws when a load equal to 10 per cent. of the required ultimate breaking strength shall have been applied, and the final length shall be the distance between the jaws at the time of rupture. The zero length shall be as near 60 inches as possible. The fracture shall be between the bench marks in the case of wire larger than 0.204 inch in diameter and between the jaws in the case of smaller wire, and not closer than 1 inch to either bench mark or jaw. If upon testing a sample from any coil of wire the results are found to be below the values stated in the table, tests upon two additional samples shall be made, and the average of the three tests shall determine acceptance or rejection of the coil. For wire whose nominal diameter is between listed sizes, the requirements shall be those of the next larger size included in Table 14.

Electric resistivity shall be determined upon fair samples by resistance measurements at a temperature of 20° C. (68° F.).

The wire shall not exceed the following limits:

For diameters 0.460 inch to 0.325 inch, 900.77 lb. per mile-ohm.

For diameters 0.324 inch to 0.040 inch, 910.15 lb. per mile-ohm.

TABLE 14.—*Hard-drawn Copper Wire (A.S.T.M.).*

Diameter, in.	Area.		Tensile strength, lb. per sq. in.	Elongation in 10 in., per cent.
	Square inches.	Circular mils.		
0.460	0.1662	211,600	49,000	3.75
0.410	0.1318	168,100	51,000	3.25
0.365	0.1045	133,225	52,800	2.80
0.325	0.0829	105,626	54,500	2.40
0.289	0.0657	83,520	56,100	2.17
0.258	0.0521	66,565	57,600	1.98
0.229	0.0413	52,440	59,000	1.79
				(in 60 in.)
0.204	0.0328	41,615	60,100	1.24
0.182	0.0260	33,125	61,200	1.18
0.165	0.0214	27,225	62,000	1.14
0.162	0.0206	26,245	62,100	1.14
0.144	0.0163	20,733	63,000	1.09
0.134	0.0141	17,956	63,400	1.07
0.128	0.0128	16,385	63,700	1.06
0.114	0.0102	12,995	64,300	1.02
0.104	0.0085	10,815	64,800	1.00
0.102	0.0082	10,404	64,900	1.00
0.092	0.00665	8,464	65,400	0.97
0.091	0.00650	8,281	65,400	0.97
0.081	0.00515	6,561	65,700	0.95
0.080	0.00502	6,400	65,700	0.94
0.072	0.00406	5,184	65,900	0.92
0.065	0.00332	4,225	66,200	0.91
0.064	0.00321	4,096	66,200	0.90
0.057	0.00255	3,249	66,400	0.89
0.051	0.00204	2,601	66,600	0.87
0.045	0.00159	2,025	66,800	0.86
0.040	0.00126	1,600	67,000	0.85

While the foregoing specification is virtually standard for copper line conductors there are some occasions where the grater ductility and lower resistance of a slightly softer wire are preferred. Such wire is also covered by a specification of the Society and is termed "Medium Hard-drawn." As it is annealed at some period between passes in the wire-mill the properties of medium hard wire are not consistently maintained between quite such narrow limits as the hard-drawn material. Tensile strength of wires within the working range is about ten per cent. lower than the hard-drawn figures. Electrical resistivity will not exceed the following limits at 20° C. (68° F.).

For diameters....0.460 inch to 0.325 inch
896.15 lb. per mile ohm
For diameters....0.325 inch to 0.040 inch
905.44 lb. per mile ohm

According to some authorities medium hard copper is preferable because it is less liable to surface nicks or kinks when being handled by construction crews in the field.

Since virtually all line conductors are stranded it is pertinent to refer to the specification of the *American Society for Testing Materials* relating to bare, concentric-lay copper cables. The following extracts cover the main features.

"1. *Products Covered:* These specifications cover bare concentric-lay cables made from round copper wires laid helically around a central core in one or more layers. The central core shall be made of wire having the same quality and temper as the concentric layers, unless otherwise especially provided for in separate specifications governing the individual case.

"2. *Requirements of Wires:* The copper wires entering into the construction of standard concentric-lay cable shall, before stranding, meet all the requirements of that one of the Standard Specifications of the American Society for Testing Materials for Hard-Drawn or Medium-Hard-Drawn Copper Wire.

"3. *Brazes:* Brazes may be made in the wire when finished and ready for cabling. Such brazes shall be made in accordance with the best commercial practice. No brazes in cable made from hard, or medium hard-drawn copper wire may be closer together than 50 ft.

"4. *Pitch and Lay:* The pitch of standard cable shall not be less than 12 nor more than 16 diameters of the cable, and the lay may be right- or left-handed, unless one direction of lay is specified by the purchaser.

" 5. *Testing:* Tests for the physical and electrical properties of the wires composing cables made from hard-drawn or medium hard-drawn wire may be made before but not after stranding.

" Experience indicates that the tensile strength of concentric-lay copper cable of standard pitch is at least 90 per cent. of the total strength required of the wires forming the cable.

" 6. *Weights and Area:* For the purpose of calculating weights, cross-sections, etc., the specific gravity of copper shall be taken as 8.89 at 20° C. The resistance and mass of a stranded conductor are greater than in a solid conductor of the same cross-sectional area, depending on the lay (that is, the pitch of the twist of the wires). Two per cent. shall be taken as the standard increment of resistance and of mass. In cases where the lay is definitely known, the increment shall be calculated and not assumed.

" 7. *Variation in Area:* The area of cross-section of the completed cable shall not be more than 2 per cent. below the area specified, as determined by weight.

" 8. *Construction:* The area of cross-section, number and diameter of wires in standard cable shall be as specified in table

" 9. *Packing and Shipping:* (*a*) Package sizes for cable shall be agreed upon in the placing of individual orders.

(*b*) The cable shall be protected against damage in ordinary handling and transportation.

" 10. *Inspection:* (*a*) All testing and inspection, both of individual wires entering into the construction of the cable, and of the completed cable, shall be made at the place of manufacture. Tests on individual wires shall be made on samples taken before cabling, and not on wires removed from the completed cable except as provided in Section 5.

(*b*) The manufacturer shall afford the inspector representing the purchaser all reasonable facilities to satisfy him that the material conforms to the requirements of these specifications.

TABLE 15.

Area of cross-section, circular mils.	Approximate A.W.G. or B. & S. gauge sizes.	Number of wires.	Diameter of wires, mils.
2,000,000	...	91	148.2
1,900,000	...	91	144.5
1,800,000	...	91	140.6
1,700,000	...	91	136.6
1,600,000	...	91	132.6
1,500,000	...	61	156.8
1,400,000	...	61	151.5
1,300,000	...	61	146.0
1,250,000	...	61	143.2
1,200,000	...	61	140.3
1,100,000	...	61	134.3
1,000,000	...	61	128.0
950,000	...	61	124.8
900,000	...	61	121.5
850,000	...	61	118.0
800,000	...	61	114.5
750,000	...	61	110.9
700,000	...	61	107.1
650,000	...	61	103.2
600,000	...	37	127.3
550,000	...	37	121.9
500,000	...	37	116.2
450,000	...	37	110.3
400,000	...	19	145.1
350,000	...	19	135.7
300,000	...	19	125.7
250,000	...	19	114.7
212,000	4/0	7–19	173.9–105.5
168,000	3/0	7–19	155.0– 94.0
133,000	2/0	7	138.0
106,000	1/0	7	122.8
83,750	1	7	109.3
66,400	2	7	97.4
52,600	3	7	86.7
41,700	4	7	77.2
33,100	5	7	68.8
26,300	6	7	61.2
20,800	7	7	54.5
16,500	8	7	48.6

" 11. *Concentric-Lay Cable:* A single conductor cable composed of a central core surrounded by one or more layers of helically laid wires.

" 12. *Lay:* The lay of a cable is the length expressed in inches for each complete turn of the wire around the axis, measured along its axis.

" 13. *Direction of Lay:* The direction of lay is the lateral direction in which the strands of a cable run over the top of the cable as they recede from an observer looking along the axis of the cable."

Notwithstanding the extensive use of aluminum-steel conductors during the last fifteen years, there has been, as yet, no specification prepared to standardize these cables in the United States, although they are covered by National specifications in Germany, France and Great Britain. As a model specification the following is submitted and has been found adequately to meet the requirements for almost any conditions. Simple tests only are called for and the paragraphs are designed to avoid ambiguity in every way possible. It will be observed that torsion, bending and wrapping tests are excluded. This is believed to be in the best interest of the subject since tests of this kind are very uncertain and the elongation figure gives a more consistent measure of the ductility of the wire whether steel or aluminum.

Specification for Aluminum-Steel Conductors.

1. *Scope.*—This specification applies to steel-cored aluminum conductors furnished by the ..... Company and its associates.

2. *Construction.*—The cables shall be made up of circular wires in concentric layers, the direction of stranding being reversed with each successive lay. Standard strandings are given in Table 16 of the Appendix.

3. *Stranding Lay.*—The stranding shall be in accordance with good manufacturing practice so that the increase in mass and resistance due to stranding shall not exceed two per cent.

4. *Tolerance.*—The individual wires shall not vary from the specified diameter by more than two per cent. nor shall measurements made at different angles on the same section vary by more than two per cent.

5. *Ultimate Strength.*—Ultimate strength of both the aluminum and steel wires shall be in accordance with Table 17 of the Appendix, and shall be measured on ten-inch lengths of wire tested between the grips of a standard testing machine. The wires shall be tested before stranding. In calculating the area of the steel wires the thickness of the galvanizing shall be included.

6. *Elongation.*—The ultimate elongation of both the steel and the aluminum wires shall be in accordance with Table B of the Appendix and shall be measured on the samples tested for ultimate strength. The fractured wires shall be closely fitted together and the elongation measured with a vernier caliper.

7. *Yield Point.*—Samples of wire when subjected for a period of one minute to a load equivalent to sixty per cent. of the guaranteed ultimate strength in the case of aluminum and seventy per cent. of the guaranteed ultimate strength in the case of steel wires shall show no permanent set on removal of the load. The wire shall be deemed to have complied with this requirement if the permanent set does not exceed 0.1 per cent. of the original length between gauge marks.

8. *Galvanizing.*—The steel wires shall be coated with a reasonably smooth uniform coating of pure zinc which shall withstand four successive immersions of one minute each in a saturated solution of copper sulphate as provided in the rules of the American Telephone and Telegraph Company. Wires of .080 inch diameter and smaller shall be required to withstand only three such immersions however.

9. *Electrical Resistivity.*—At standard temperature of 20 degrees Centigrade the resistivity of the aluminum wires shall be not greater than .07766 ohm (meter gram) corresponding to 60 per cent. of the International annealed copper standard of conductivity.

10. *Splices.*—The individual aluminum wires may be welded in course of manufacture provided that (*a*) the ultimate strength of such a weld shall be not less than 80 per cent. of the specified ultimate strength of the wire and (*b*) no such weld shall occur at a less distance than fifty feet from another such weld in the finished cable. No splices or welds shall be made in the steel wires.

11. *Finish.*—All wires shall be free from imperfections of manufacture and surface defects not consistent with the best commercial practice.

12. *Inspection.*—Authorized inspectors shall be permitted to visit the works during the manufacture of the cable. Official inspection shall take place at intervals by mutual arrangement. The inspector shall take samples from any coil of wire for test, but unless otherwise agreed the number of coils tested shall not exceed ten per cent. of the total production. If a sample of wire is found to be below the guaranteed figures two other samples shall be cut from the same coil and tested. The average of the three shall determine the acceptance or rejection of the coil.

APPENDIX.

TABLE 16.—*Stranding.*

Aluminum Area, Circular Mils. up to	Number of Strands. Aluminum.	Steel.
83,700	6	1
133,000	6	7
550,000	30	7
1,000,000	54	7

TABLE 17.—*Ultimate Strength and Elongation.*

Diameter of wire.	Aluminum.		Steel.	
	Lb. sq. in.	Elongation, %.	Lb. sq. in.	Elongation, %.
0.070	—	—	200,000	4
0.100	27,500	1.75	180,000	5
0.125	25,500	1.9	180,000	5
0.150	24,000	2.0	180,000	5
0.175	23,500	2.2	160,000	6
0.200	22,500	2.3	160,000	6
0.225	20,500	2.5	—	—

The British Engineering Standards Association has recently issued a comprehensive specification on copper wire and cable for overhead transmission, and it is expected that this specification will be widely used because of the very practical manner in which the tables are drawn up and of the reliable data which they incorporate. In the specification the following mechanical and physical constants for hard-drawn copper are standardized:

Density at 60° F	8.890		
Weight per cubic foot	554.98	lb.	
Linear expansion coefficient	9.222×10^{-6}	(° F.)	
Modulus of elasticity	18×10^{6}	lb. sq. in.	
No. of strands in cable up to	0.075	sq. in.	3
" " "	0.25	"	7
" " "	0.50	"	19
" " "	0.75	"	37

Some may be found to criticize the use of three wire cables which are open to objections already pointed out. Furthermore the inclusion of both "standard" and "calculated" areas in the tables may be confusing, but it is nevertheless explicit, and tends towards a redundancy rather than insufficiency of information. A specification has also been issued by the British Electricity Commissioners which very briefly summarizes the requisite figures for copper and aluminum transmission wire as follows:

TABLE 18.—*Specification for Wire (Electricity Commissioners).*

	Copper.	Aluminum.
Tensile strength (lb. sq. in.)	54,000	25,000
Elongation on 10 in.	1 per cent.	4 per cent.
Modulus of elasticity	18×10^{6}	10×10^{6}
Minimum size of conductor (sq. in.)	0.0098	0.0237

This specification is very brief and takes no account of the variation of tenacity and elongation with the size of the wire. Furthermore, there is reason to doubt whether the elongation of 4 per cent. on aluminum wire can be attained on a commercial product as the average test shows about one half this amount, and for small wires even less. Some information should be appended covering the method of making the test, whether before or after stranding; time of applications of load and similar details.

A further step has been taken by the British Engineering Standards authority in issuing a specification on aluminum and aluminum-steel conductors. In it are set forth the following constants for aluminum wire:

TABLE 19.—*British Standards for Aluminum Wire.*

Density at 60° F.	2.705
Weight per cubic foot	168.87 lb.
Linear expansion coefficient	12.6×10^{-6} (° F.)
Modulus of elasticity	9.6×10^{6}
Number of strands in aluminum cable	
up to 0.05 sq. in.	3
" " 0.25 " "	7
" " 0.65 " "	19
" " 1.25 " "	37

The following values of stranding and elasticity are those on the specification relating to aluminum-steel conductors.

TABLE 20.—*British Standard Stranding.*

Area up to sq. ins.	Number of wires.		Modulus of elasticity.
	Aluminum.	Steel.	
0.09	6	1	12.51×10^{6}
0.125	6	7	11.95×10^{6}
0.45	30	7	13.45×10^{6}
0.75	54	7	11.95×10^{6}

In the British specification a wide range of values is tabulated for the tensile strength of both aluminum and steel, the former varying with the size of the wire from 28,000 lb. sq. in. down to 23,000 lb. sq. in. and the steel varying from 200,000 lb. sq. in. down to 160,000 lb. sq. in.

It will be noted that some of the derived constants in the British specification are at variance from those used in American practice in composite cables. These divergences are due to slightly different determinations of the fundamental properties of the wire but are not of a serious nature.

CHAPTER II

INSULATORS

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Manufacture of Porcelain.—There appears to be little need to consider any insulating material other than porcelain at the present stage of the art, although it will be conceded that one of the most valuable possible inventions would be that of an insulating material having the physical characteristics of a metal. At present, high electrical and mechanical properties unfortunately do not coincide in the same substance, and a compromise must be made. None of the elements in the transmission line has duties as severe as those pertaining to the insulator, whether of the pin or suspension type. Not only do the insulators have to withstand all the physical and thermal conditions which the other parts of the line must sustain, but they must simultaneously insulate a working voltage sometimes as high as 130 kilovolts from ground, in addition to resisting the effect of the occasional arcing ground and the consequent high-frequency disturbance and high temperature. Glass and synthetic substances have been employed for insulator manufacture, but the first is too much affected by temperature changes, and the latter are generally electrically inferior as well as sometimes being hygroscopic.

In the production of porcelain, clay is burnt with an admixture of feldspar and quartz. At the appropriate temperature the quartz will fuse, permeating the porosities of the mass and securing vitrification, the clay being (according to one theory) partially converted to sillimanite. The function of the feldspar is to act as a flux to assist in the fusion of the quartz. Of all the manifold varieties of clay, English ball clay from Cornwall is generally used, because of its superior plasticity, kaolin or China clay being next in favor. The latter burns white when fired, for which reason it is sometimes preferred, but this quality has little value as compared with plasticity. Feldspar is usually selected with a view to high potash content rather than soda. The proportions usually quoted are: clay, 50 per cent., potash feldspar, 30 per cent., and quartz or silica, 20 per cent., but individual makers vary these proportions between certain limits. The feldspar and quartz are ground to from 140 to 200 mesh, the final grinding being in a pebble mill. Very thorough grinding has been found essential to the production of high quality porcelain, as it assists in more thorough permeation and vitrification with a lower firing temperature. The 200 mesh material is therefore superior to that of 140 mesh, which is probably the lowest permissible grinding limit. In some mills the ball clay is also ground, but generally it is sufficiently fine in consistency, and better preparation of the other constituents is obtained by leaving the clay out of this operation. Meantime, the clay is separately treated by mixing with water in a

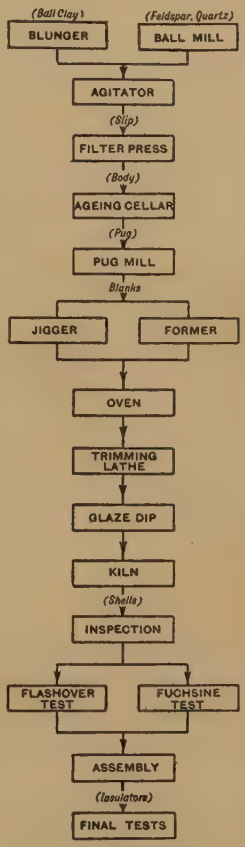


FIG. 20.—Outline of porcelain insulator production.

blunger, which secures thorough agitation by means of rotary paddles revolving in opposite directions. When sufficiently blunged, the clay slip is run into an *agitator,* where the ground feldspar and flint are also introduced, and the whole thoroughly mixed. The amount of water to be added is carefully controlled, so that the proportions in both ingredients are equal, taking into account the original moisture content of the raw materials. The next operation is the *filter pressing* or lawning of the slip as it is pumped from the agitator. Generally two sets of lawns are used of successive degrees of fineness, and very careful selection of the lawn is necessary to guard against breaking down or the transfer of threads or hairs into the body. On removal from the presses the body is in the form of leaves some 1½ inches thick, and 24 inches square, and contains from 20 per cent. to 25 per cent. moisture. These leaves are stacked in a dark storage cellar held at a high degree of humidity to age. Various periods are used for *ageing,* sometimes as long as twenty-one days, whilst the possibility of accelerated ageing by chemical action has not been overlooked. In some mills the uniformity of the product is controlled by careful design of the pumps leading from the slip tanks to the filter presses, so that no air can reach the mixture and the subsequent leaves will be entirely free from air bubbles or "blebs." Where this operation is carefully handled, there is said to be no need for subsequent ageing. Obviously a good deal of space and capital are tied up in the ageing cellar, and the tendency is to achieve good porcelain with a shorter process.

Pugging is the next operation in order, and consists in stirring the plastic body mixture in a pug mill, which is a vertical cylinder having a central shaft and propeller-shaped blades revolving in opposite directions, which not only cut, but squeeze, the material downwards. This mill is kept continuously charged, and the pug (of the consistency of putty) is extruded at the foot of the mill in a cylinder of 6 to 9 inches diameter. Suitable lengths are cut from the mass, each of which will just fill a mould. In the design of the pug mill the chief difficulty to

overcome was that of lamination by which the pug would fall into planes corresponding to the faces of the propellers. This problem has now been satisfactorily solved, and the pug from a modern mill is as near as possible homogeneous.

The clay is now ready for *forming,* and two methods are employed for this operation. In the first method, jiggering, the plaster of paris mould containing the pug is spun around on a vertical axis just as in the traditional potter's wheel, and a wood template is lowered into it to form the interior of the shell. Machine forming is more in favor at the present time, except for very deep or narrow shells. In this process the mould is stationary and the form rotates rapidly, being lowered into the shell with the same mechanism as a sensitive drill. A steel die is used for the form, and it is oiled and kept hot by a gas flame. In this operation a definite pressure is exerted on the clay, whereas in the jigger the action is one of scraping; moreover, the steel die will yield more complicated contours without tearing. Of course, re-entrant curves and grooves cannot be formed, and must be turned in a lathe in a later operation.

Apart from machine forming, *casting* is sometimes employed as a method of producing large porcelain shells. The slip or liquid body is poured into plaster moulds in a similar manner to the casting of metal. As the dry plaster rapidly absorbs the water in the clay, the slip must be constantly fed in until the shell is set solid. Large blanks of relatively thin sections are best produced in this manner, other shapes being formed on a press.

In *drying* the formed shells the chief requirement is that they shall not become " skin dried," as this would seal the moisture in the interior with evil results. The preliminary drying-room is, therefore, kept both warm and humid, so that reasonably uniform evaporation may be ensured. In some mills a tunnel dryer is used, through which the ware travels and which provides successive degrees of dryness. Other manufacturers do not dry immediately after forming, but store the ware in the mill at normal temperature for from twenty-four to forty-eight

hours, afterwards trimming or turning where necessary, and then drying in the oven. Uniform drying is essential to obviate distortion as the ware shrinks in the mould.

After drying, the ware can be removed from its mould and trimmed, being turned in a lathe like wood. Those surfaces of the shell which will have to be cemented are now sanded with sharp flint grits. *Glazing* is then performed by simply dipping the shells into a clay wash with a high proportion of feldspar. The sanded surfaces are kept free of glaze by first painting with paraffin. The coloring matter added to the glaze is generally manganese dioxide, which produces a rich brown tint, but in some cases a white glaze is preferred. Immediately following glazing, the shells are dried at 250° F. The next operation is *firing* in the kiln, in which the constitution of the material is entirely changed and the finished product is achieved. The individual shells are packed in rough earthenware saggers in such a way that they do not rest on the glaze, and the saggers are piled in the kiln. Generally about one day is occupied in charging the kiln, three or four days in firing, and two days in unloading, so that the cycle covers about one week. Temperature is brought up to about 2,400° F., and must be controlled with reasonable care. Pyrometric or Seger cones form the basis of temperature control. These cones are mixed of certain finely ground minerals, such as feldspar and kaolin, so proportioned that at a definite temperature the appropriate cone (which is about 2½ inches high) will fuse and drop over till its vertex touches the clay base. Cone No. 10 is the most important from the viewpoint of the porcelain manufacturer, as it deforms at 2,426° F. A series of cones is set up in the kiln where it can be observed from outside and the firing controlled.

Under-firing results in porosity, and over-firing in brittleness; the range of temperature must not be overstepped, therefore. According to Dr. Frank H. Riddle, the well-known ceramist, a good deal of success has attended the operation of the tunnel kiln which is employed by a very large manufacturer of insulators. In this type the process is continuous, as the ware travels

through on cars at a predetermined rate, reaching the maximum firing temperature in the middle of the kiln, and from thence gradually cooling until the cars emerge. Of a total of four days in the tunnel kiln, about eight to ten hours are passed in the firing chamber; prior to this the ware is approaching and heating up, and subsequently it is receding and cooling down.

After emerging from the kiln, the work is inspected and given an electrical test to eliminate defective shells. One shell in the firing batch is submitted to a penetration test for under-firing or porosity. It is broken and the pieces immersed in a solution of fuchsine (a coal-tar derivative with a pronounced red color) under a pressure of not less than 200 lb. per square inch. After subsequent washing in alcohol and drying, the permeation of the red dye will indicate any porosity if the specimen is under-fired, and lead to the rejection of the batch. Under-fired porcelain may result not only from low-temperature firing, but from insufficient feldspar, and the converse holds true for over-fired material.

The fuchsine permeation test has been criticized as being no true criterion of the quality of any shells in the firing batch except the one which has been tested and therefore destroyed. It is believed that this and other criticisms arise from the fact that formerly the test was not made sufficiently severe. In the British Standard Specification for high tension insulators the requirements call for immersion of the broken shell for twenty-four hours under a pressure of 2,000 lb. square inch. An important group of utilities in the United States require a pressure of 5,000 lb. under similar conditions.

The next operation is *cementing,* because in most cases pin type insulators consist of a series of shells cemented together, whilst suspension discs must be connected to their hardware by the same medium. Pure neat Portland cement is used, freshly mixed with about 20 per cent. water, and after assembly the ware is permitted to set in an atmosphere of steam. The object is to set the cement at a temperature higher than any which will be encountered in service, with the result that no further

dehydration, cracking or loosening is possible. As many insulator failures in the past have been traced to the expansion and contraction of the hardware, special means are adopted to counteract this. In a suspension disc of the conventional type, having a steel pin inside and a malleable iron cap outside the shell, the exterior of the pin as well as the interior of the cap are treated with a bitumastic paint. This will provide an elastic diaphragm which will yield sufficiently to take up the difference in expansion between the metal and the porcelain.

Properly mixed and fired, porcelain will have a tensile strength between 3,000 and 4,000 lb. per square inch, with a strength in compression of about twenty times as great. Special porcelains are now being produced which are considerably stronger in tension, but if other difficulties could be eliminated and the material kept in compression, the ideal insulator would be evolved. Unfortunately, designs for transmission work do not generally permit of this, although some part at least of the load should be transmitted by compression. The following tensile test figures relate to porcelain test pieces of different size, the figures being due to F. H. Riddle and J. S. Laird:

TABLE 21.—*Ultimate Strength of Porcelain.*

Area, sq. ins.	Tensile strength, lbs. sq. in. Standard.	Special.
½	5,500	8,400
1	5,000	7,000
2	4,200	6,100
4	3,000	4,200

In its physical properties natural sillimanite is an almost ideal insulator material, only its scarcity and cost prohibit its use for large pieces. At present the commercial use of this material is confined to ignition plugs.

Selection of Type.—In the early days of power transmission the art relied entirely on the previous experience of telegraph engineers and the wires, insulators and poles were little, if any, different from those common on telegraph lines. As voltage was increased on successive lines, the porcelain insulator,

mounted on a pin and carrying its wire on a top groove, became larger and heavier; compound assemblies of two or more shells were cemented together and mounted on a steel pin. When operating potential was increased to 110 kilovolts, it was thought necessary to introduce a new type, namely, the suspension insulator, in which a series of porcelain discs are linked together in a flexible chain and suspended from the crossarm. In this type the number of discs could be selected for any given local or climatic condition. Most engineers agree in using the pin-type insulator for 66 kilovolts or less, and the suspension type for 110 kilovolts or more, but there is a field between the two limits where either type may be used. Certain reasons, however, tend to favor the suspension type. In the first place, it has often been found necessary to increase the operating voltage of the line after it was first installed; with the suspension assembly the addition of the appropriate number of discs is an easy matter. Further, the flexibility of the string relieves the pole or tower of a great proportion of the unbalanced load in case a wire breaks, whereas owing to the rigid character of the pin-type unit, the shock may bend the pin or twist the crossarm. On the other hand, an advantage of the pin insulator lies in its requiring a shorter pole or tower because it is mounted on, not under, the crossarm. Generally, the operating experience is in favor of the suspension units for mechanical reasons, and in view of the fact that the great majority of transmission systems now being planned or built in various parts of the world are designed to operate at more than 66 kilovolts, it may be said that the suspension type of unit will sooner or later become universal.

Pin-type Insulators.—Design of the pin-type insulator is mainly controlled by electrical considerations: its contour is designed to give the maximum leakage path with a rational flashover distance and to yield a reasonably uniform flux distribution. The tendency of recent years has been to diminish the flashover distance so that the ratio of puncture to flashover voltage is much higher. A larger number of cemented shells especially de-

signed to minimize strains is also a feature of later types of pin insulator. The chief mechanical problems are concerned with the pin and the conductor attachments. In all the earlier transmission lines a pin of hard locust wood was favored; this material was as nearly indestructible as any organic substance can be. Threaded steel pins were then introduced in the larger units, and trouble was experienced due to the expansion of the pin cracking the porcelain. Nevertheless, the steel pin became permanent following the introduction of steel crossarms and towers, so that means for compensating the expansion strains became necessary. A device commonly used with large insulators is to set a threaded brass liner in the pin hole by the use of cement, and detachable brass or lead thimbles are also in wide use, but it is more usual to set the pin direct in the insulator with Portland cement. In some cases a steel pin is provided with an impregnated wood top carrying the thread. This obviates the troubles arising from screwing a steel pin directly into a porcelain insulator (which is, moreover, contrary to certain standard specifications). In any event, the steel pin should be sufficiently liberal to carry the load if a wire breaks. The maximum tension occurring in a wire of 0.20 square inch copper section would approximate 5,000 lb., and unless the conductor slips through the tie wire this tension will be imposed at the top of the pin. If the pin should break or be distorted it will probably crack the insulator. In some installations the insulator pin is not bolted through a wood or steel angle crossarm, but terminates in a sleeve which is bolted around a tubular crossarm of steel. Here the first thing to yield will probably be the sleeve, which is pulled around in the direction of the load without any part of the assembly being distorted or broken. A broken wire under maximum load is an abnormal condition, but it must be allowed for, and the essential rigidity of the pin insulator assembly is a disadvantage where heavy and sudden stresses may be met. To a certain extent the fastening of the wire to the insulator groove is part of the same problem. In the event of an abnormal load it is best that the conductor should slip through

the tie wire. For this reason the use of clamps is almost universally regarded as unsatisfactory. Not only does a clamp hold the wire too tightly when it is least required to do so, but it is generally either too tight or too loose around the head of the insulator. In the first case it may crack the porcelain, and in the second it will chatter and possibly fail by fatigue. Annealed wire of the same composition as the conductor should be used to tie the cable down, and the diameter of the tie wire should not be less than 0.20 inch and preferably 0.25 inch for large cables. In many installations tie wire of far too small a size is used, consequently the assembly is weak and may easily be burnt or pulled off. Wire of the above size will make a tie which is far below the conductor in tenacity, but it will hold up to all normal conditions of operation.

In its large sizes the pin-type insulator is of a high degree of mechanical reliability. Cracking of the outer shell due to a rain shower on a hot day is now rarely experienced. For 55 kilovolts or higher the insulator unit is usually an assembly of three or more shells cemented together, and strains arising from the swelling of the cement are neutralized by coating the intermediate surfaces with paint having a bitumen base.

Although, as already mentioned, the desirable operating limit of the pin insulator is reached at about 60 kilovolts, remarkable success has attended its use at much higher voltages in a few isolated systems. Writing of the 90-kilovolt lines of the Toronto Power Co. from Niagara Falls to Toronto, Paul Ackerman says:

> "Voltages of 60,000 to 70,000 are considered the practical operating limit for transmission lines using pin-type insulators, because it has always assumed that safe operation necessitates a minimum of wet flashover of at least two to two and a half times the maximum line voltage, and because 150,000 volts to 160,000 volts wet flashover is the practical limit which can be obtained with pin-type insulators of the customary shape. If an attempt be made to build a pin-type insulator of higher wet flashover, it will

become unduly large and heavy, or if built in detachable parts it will become mechanically weak by reason of the excessive height. The adoption of such a high safety factor as mentioned has been chiefly influenced by the enormous number of insulator failures experienced in the past and now, fortunately, being reduced.

"The new insulator differs chiefly in having thicker shells and more rounded shapes intended to avoid internal stresses. Preference was given to the three-shell insulator, as compared with the four-shell insulator, to obtain heavier individual shells at a fixed permissible total weight. The shells were glazed all over, and had smooth sand-glazed surfaces to eliminate surface cracks and moisture penetration. About a thousand insulators were installed on the 60,000-volt lines during the winter season of 1916 to 1917 in order to obtain operating experience." *

The main point demonstrated by Ackerman by practical trial and by operating records extending over several years was the fact that the design of pin-type insulators has been improved and their operating characteristics bettered by employing a lower safety factor against flashover coupled with a compact contour and high quality porcelain. In connection with this an adequate system of protective relays is used which suppress any power arc virtually before it becomes destructive. These factors combined have made it possible to operate with 90 kilovolts on pin-type units.

The foregoing statements, however, do not endorse the adoption of pin insulators for new construction at this voltage, but show a way to raise the voltage of existing lines with economy.

Mechanically the suspension insulator is superior to the pin type by reason of its flexibility. An abnormal load on a wire due to unbalanced ice coating, a burn-off, or otherwise, is immediately compensated by the insulator swinging out in the direction of the load. With any suspended wire on a given span the tension is profoundly affected by a small difference in length,

* *Electrical World,* vol. 80, p. 1440.

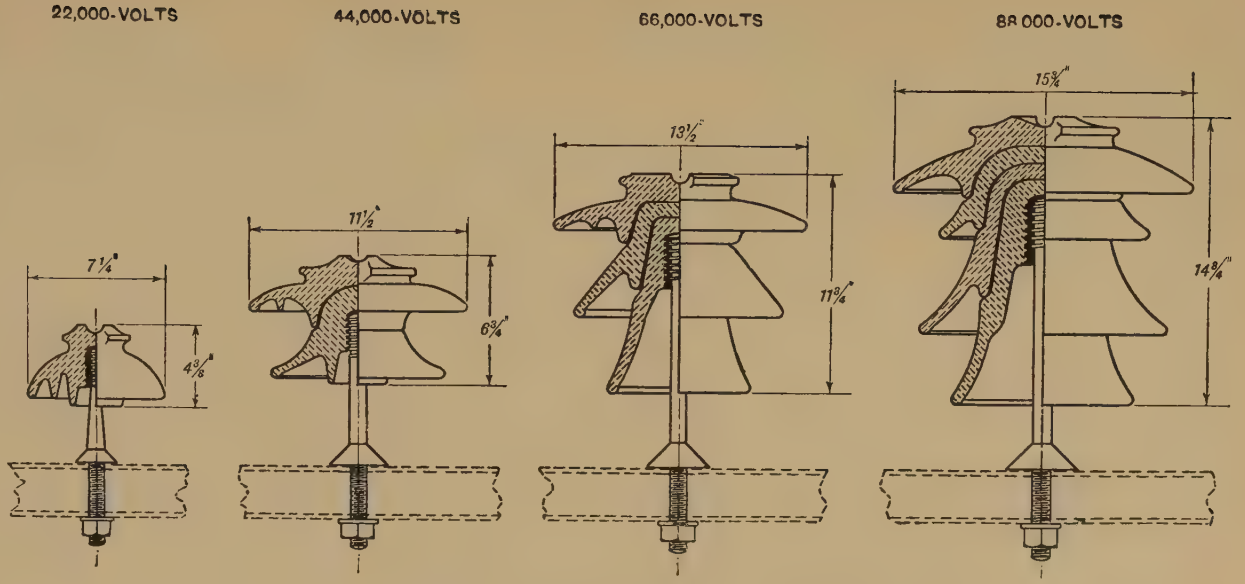


FIG. 21.—Proportions of pin-type insulators for various voltages.

so that an increased length will immediately reduce the stress to a normal figure. This fact has opened the way to the stringing of modern transmission lines with heavy conductors carrying a high degree of mechanical tension on long spans, and except at dead ends the maximum load will not be transmitted to the crossarms. The individual discs which make up the suspension insulator have been developed in three different forms, namely, the metal cap, the link, and the spider designs. This nomenclature defines the type of hardware by which the porcelain discs are mounted and assembled together.

Suspension Insulators, Metal Cap Design.—This design has probably come into the most extensive use up to the present time. Cement is used for the assembly of the steel pin and malleable iron cap, and many insulator failures in the past have been traced to hydration and swelling of the cement. It is believed that this trouble is virtually eliminated in the modern insulator, but there is still a tendency to regard a cementless assembly as superior. Nevertheless the ease with which discs are assembled or replaced and the universal standardization of fittings are valuable factors in favor of the metal cap type. Electrical properties are inherently satisfactory, and mechanically the metal cap insulator is made in two forms, regular and high strength. As already mentioned, the tensile strength of porcelain is about 2,500 lb. per square inch, but in order to have a margin for inconsistency the design value is usually assumed at 1,500 lb. The area of the porcelain under tension in a disc of the present type is some 6 square inches, giving a maximum tension load of 9,000 lb. per insulator. In positions where heavy loads are carried, an augmented size of unit is employed which has approximately double this ultimate strength. Design of this insulator being more liberal in every way, its cost and weight are higher, and it does not at present replace the standard suspension unit except in strain positions; but with the heavy conductors now coming into use, there is a tendency to design the transmission line with high strength units throughout.

A high-working tension on a cemented insulator has a tend-

ency to accelerate electrical deterioration, and the maximum load is usually calculated at one-third the ultimate, or, in American practice, 3,000 lb. for the suspension and 6,000 lb. for the strain insulators. Considerable work has been done to develop a satisfactory pin head which would not be loosened by the cyclic temperature changes nor by any load up to the mechanical

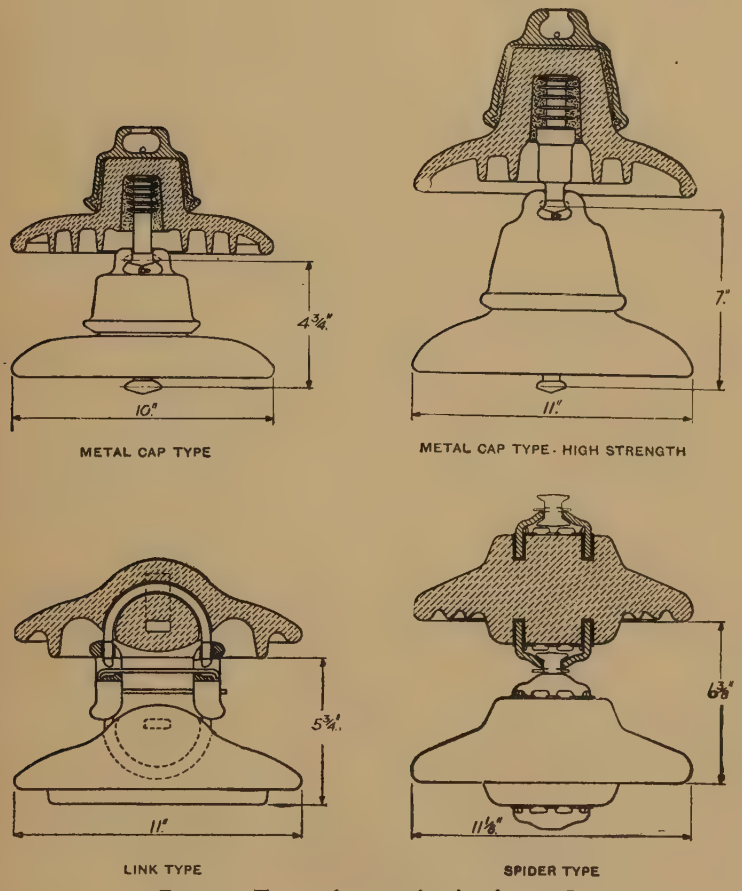


FIG. 22.—Types of suspension insulator.—I.

limit of the porcelain. A corrugated stem has been the longest in use, but it is not mechanically perfect, and has been largely replaced by a pin, the embedded portion of which formed one

or two cone frustra, so designed as to convert the pull partly into a compression on the porcelain. One manufacturer has developed a pin carrying a series of three or four wide flanges ⅛ inch thick; this device, when coated with an elastic varnish and embedded in cement, gives a pin which yields slightly, and is less affected by shock or temperature changes. It furthermore has the advantage that under load it exerts no lateral thrust, tending to split the porcelain shell.

One of the criticisms to the use of cement in an insulator has referred to the swelling of the cement due to hydration at high temperatures when in service. This has led to excessive strains and subsequent failure of the porcelain shell, but is now believed to have been overcome by the regular manufacturing practice of setting the cement in an atmosphere of high temperature steam. Provision must also be made for expansion of the stud with high temperature, which also exerts a strain through the cement, tending to crack the porcelain shell. The metal cap is also subject to strains with rapid changes in temperature such as occur when rain falls on a hot day. In such a case the cap will contract and tend to crush the porcelain. This has not been found as serious as the expansion of the pin above referred to, because the stress is more evenly distributed, but the combination of strains due to heating and cooling make the mechanical problems of insulator design very difficult. Electrical trouble is usually associated with mechanical, so that when porcelain is under a local excessive strain, puncture may follow. It has been obvious that some form of elastic layer was desirable between the metal and the cement, and a coating of this nature is now generally used. Paraffin wax has been used for coating the stud as well as the top of the shell under the cap. Bitumastic paint is also employed, and in some instances a cork disc on top of the stud, as well as in the head of the cap. Virtually all makers have now recognized the importance of an elastic layer, with the result that little or no cracking due to temperature changes is now reported. Tests have been made by plunging the insulators alternately into cold and boiling water for a large

number of cycles, maintaining during the test a high degree of mechanical tension, and as a result surprisingly little deterioration has been found.

A considerable amount of development work has been done by German insulator makers. The tendency has been to round

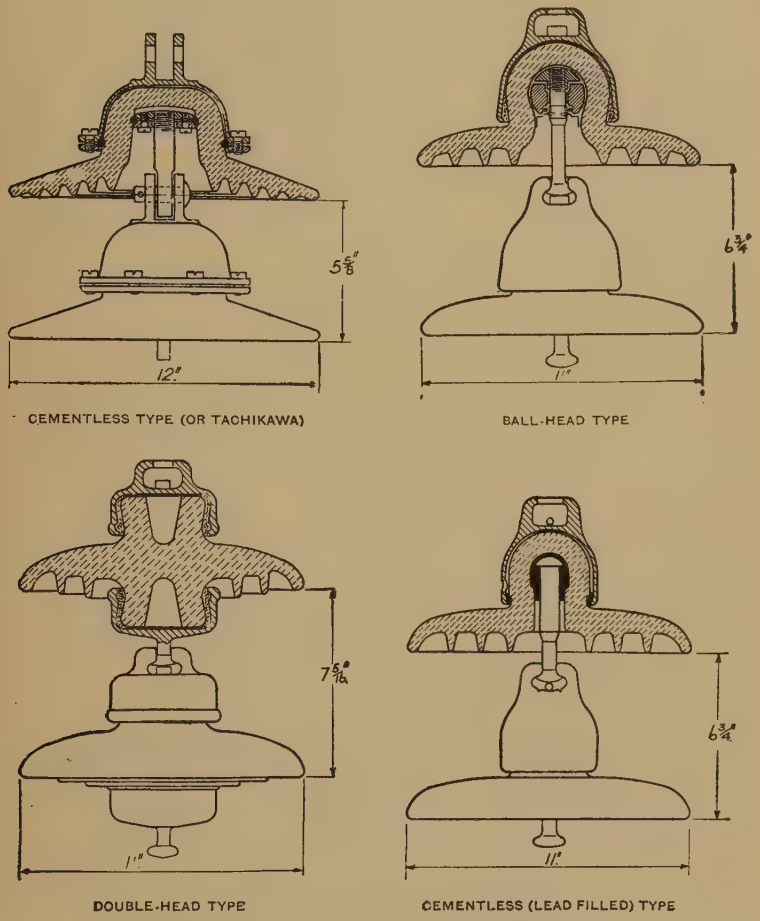


FIG. 23.—Types of suspension insulator.—II.

off the head of the unit, so as to form a hemisphere; in this way both mechanical and electrical stresses are better distributed. The next step was to introduce a layer of copper or graphite

around the interior of the shell, thus shielding the cement from the permeation of leakage currents. A further development has been the "Ball-head" insulator, in which a spherical porcelain knob is seated in the insulator socket. The stud passes through a hole in the center of the knob and engages with a nut on the opposite side. The method of introducing the ball into the socket is ingenious; the ball is first fired and introduced into the shell when the latter comes from the drying oven. The latter is then passed to the firing kiln and the porcelain shrinks down upon the knob, so that the latter is held loose in the socket but cannot drop out. The nut is then placed on the knob and turned around until it is at the back, when the stud can be pushed through the hole in the knob, screwed into the nut and locked. An elastic cement is then forced into the space around the knob. In this form of insulator the chief merit is that the expansion of the stud cannot strain the porcelain because sufficient clearance is provided around it.

The elastic cement referred to consists of ordinary Portland cement, with an admixture which is a secret of the insulator makers. The effect of the mixture is to restrain volumetric changes during and after setting.

Whilst considerable progress has been made in eliminating troubles due to cement, other experimenters have turned to the production of a metal cap unit which would be assembled without the use of cement. A development of the Continent provides for seating the stud in lead or a lead alloy; at the same time, a lead ring is cast around the body of the unit and gripped by the wrought iron cap. The utility of lead is not definitely proved, however, and this practice is dependent upon the production of an alloy of virtually zero expansion coefficient. In another form of insulator a cone is set in the center of the socket, and the stud, which is split at the end, is driven up over it. The effect is to expand the end of the stud so as to fill the conical cavity in the porcelain. A seating of lead or paper is provided between the bolt and the porcelain surface. The cap is assembled in two halves by flanges and bolts, also with a liner where contact is made with the porcelain.

One of the most practical designs yet devolved for a suspension unit which incorporates no cement is due to Dr. H. Tachikawa, of the Tokyo Electric Co., in Japan. This insulator is illustrated in the figure. Of this model Dr. Tachikawa says:

> " From what has been said it is evident that of the many elements which cause deterioration, and thus affect the life of an insulator, the principal one is the change of temperature. Authors conducted several experiments on deteriorated insulators, which convinced them that the absorption of moisture is not the chief cause of deterioration, unless the insulator is very poorly fired. In any kind of

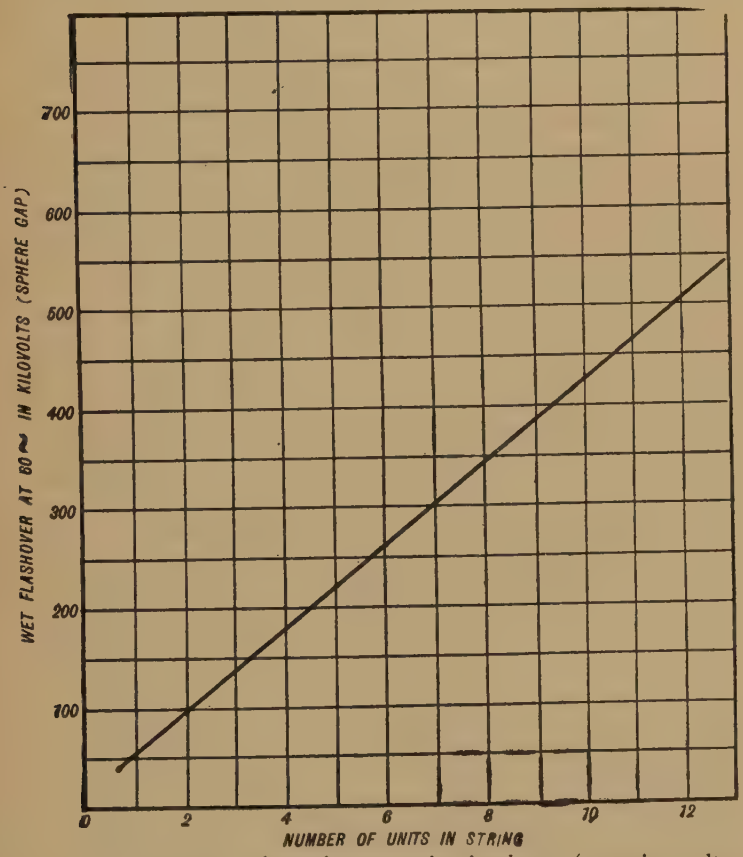


FIG. 24.—Wet flashover voltage for suspension insulators (operating voltage should not exceed one half these values).

cemented insulator the cement absorbs moisture, and becomes gradually harder and increases in volume, so that the cement readily transmits a thrust from the insulator pin to the porcelain part. The only way positively to relieve an insulator from failures of this sort is to avoid using any cement. The Inawashiro Co. has lately developed a type of insulator which does not require the use of cement, and has named it G type. About 820 of this type have been in use since 1920 on the line and in switching stations without showing a single failure, but in manufacturing this type care must be taken in securing perfect dimensions of porcelain parts to fit well with metal parts. There is a disadvantage, also, of the metal fittings costing more for this type."

The principle of the design embodies a groove inside as well as outside the unit. Into each of these grooves a ring of steel is sprung, and on to the outer ring the two-piece cap is keyed, whilst the stud is screwed into a disc held by the inner ring.

As above mentioned, the difficulty of producing porcelain shells with a small dimensional tolerance is the chief drawback to the use of assembled insulators of the types described. For this reason, the great majority of the metal cap insulators employed will doubtless continue to be of the cemented type.

Suspension Insulators, Link Type.—One of the earliest practicable forms of suspension insulator to be developed was the interlinked type. This was devised by E. M. Hewlett, of the General Electric Co., and is generally known as the Hewlett insulator. In principle the unit consists of two metal links, which are separated by a ball of porcelain. Simplified insulators of this general type use grooves in the porcelain ball, in which the copper links are seated, but in the Hewlett insulator proper the links are threaded through tunnels, which are cut in the clay shell before firing. Obviously the greatest care must be used in this operation, because the distance between the holes is small, and any irregularity due to the tool running out of truth would seriously reduce the dielectric strength of the insula-

tor. The manufacturing problems, however, are believed to have been satisfactorily solved. The links must next be designed in halves with some form of clasp, so as to permit of easy threading and assembly. Various forms and materials have been employed; copper strand, copper and bronze rod, and duralumin have been used, but the latest form of Hewlett disc utilizes a steel band, as shown in the illustration. This has ample width and section, so that the load is carried by a reasonable area of porcelain instead of merely a line, which was the case when a round section link was used. At the same time, a rectangular tunnel is used in the porcelain in which the link is carried.

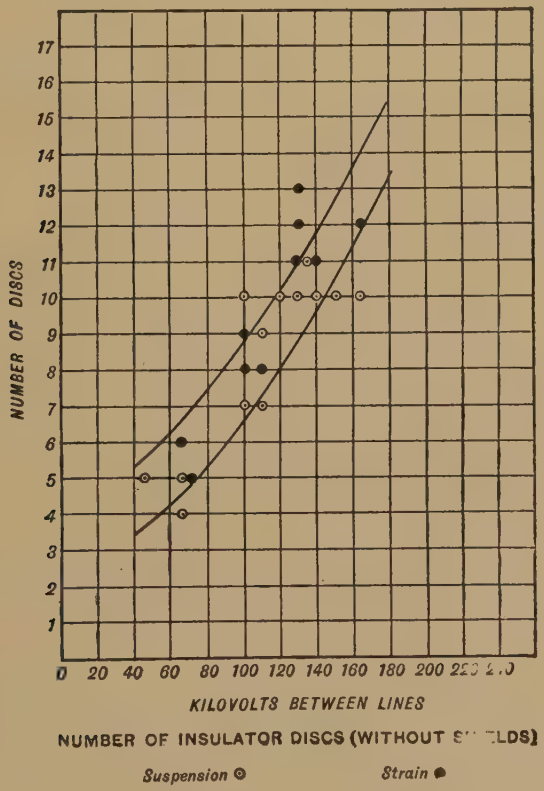


FIG. 25.—Empirical curves showing appropriate number of insulators for different voltages.

A particular merit of the Hewlett insulator, and one which is not offered by the metal cap type, is the fact that if one or two discs are shattered by an arc over, the conductor will not be dropped, because the links will not part. In early models there was a tendency for the copper links to burn through if the arc " cascaded " from one unit to another, but this is prevented now by the use of steel links, and by improved design of the assembly as a whole. Shortening up the length of string and reducing the distance from line to ground has improved the service characteristics in this respect, and the use of arcing horns or shields may contribute still further.

It can be said of the latest design that units can be easily replaced on the line, and the attachment of the links now requires little time or skill. As it is customary on many high-voltage systems to change insulator units whilst the line is alive, the ease of attachment is a very important matter, and may be the deciding factor in selection of the form to be used. Some operating companies have found the link design especially favorable for use in dead-end positions, although metal cap units are standard for suspension; the tendency is for a non-cemented unit to show greater reliability when under constant strain.

Suspension Insulators, Spider Design.—Another means of producing a cementless insulator is adopted by a large manufacturer, who uses a thick cast porcelain disc, the hardware assembly being attached to it on either side by an eight-pointed metal claw. The claw is embedded in sockets in the porcelain, but instead of filling the sockets with cement, they are poured with a special alloy of low temperature expansion coefficient. The ultimate tensile strength of the assembly is about 10,000 lb., or the same as with either of the other types; electrically this form is a little more effective, and some transmission engineers use one less disc per string when they are of the spider design. Of this pattern the manufacturers say as follows:

> " The assembly of these insulators is accomplished quickly by anchoring the metal spiders into the corrugated holes in the porcelain with a special alloy. This alloy is

poured at a temperature of 720° F., and, having a very low coefficient of expansion, fills the sixteen holes in the unit as a die-cast alloy fills the die. The tensile tests can be made a few minutes after assembly. This is an advantage to companies who have an inspector at the factory, as they can witness every step of assembly and test from the kiln car to the freight car without long delays for cement to set. Long service has also proved the great advantage of this construction over cement by the fact that in hundreds of thousands of units put in service during the past seven years we have found no evidence of cracking of the porcelain round the alloy due to temperature changes, freezing or length of service."

Electrically and mechanically these diverse types would be on a par, but in service there is a distinct bias in favor of a design which uses no cement if its other properties are acceptable.

Electrical Characteristics.—Whilst this study is concerned mainly with mechanical values, it is necessary, in the case of the insulators, to treat briefly of the electrical side of the subject. This is especially true of the suspension units which are assembled to meet specific or local operating conditions.

TABLE 22.—*Characteristics of Suspension Insulators, Ten Discs per String.*

	Metal Cap.		Link.	Spider.
	Standard.	Special.		
Ultimate strength (lb.)	9,000	18,000	8,000	10,000
Arc over (dry, kv.)	488	488	510	650
Arc over (wet, kv.)	370	370	360	450
Diameter (in.)	10	10	10	$11\frac{1}{8}$
Length of string (in.)	55	$57\frac{1}{2}$	$57\frac{1}{2}$	$63\frac{3}{4}$
Weight (lb.)	105	125	109	190

A standard porcelain metal cap insulator disc will flashover at 60 cycles with about 60 kilovolts when wet, or 90 kilovolts dry. As further units are added to the string the flashover voltage does not increase in the same ratio because of the variation in capacitance or condenser effect. A 10-unit string will

flashover at 350 kilovolts wet and about 450 dry, the latter figure being dependent upon the design, whereas the wet flashover, being a measure of the leakage path, is more nearly pro-

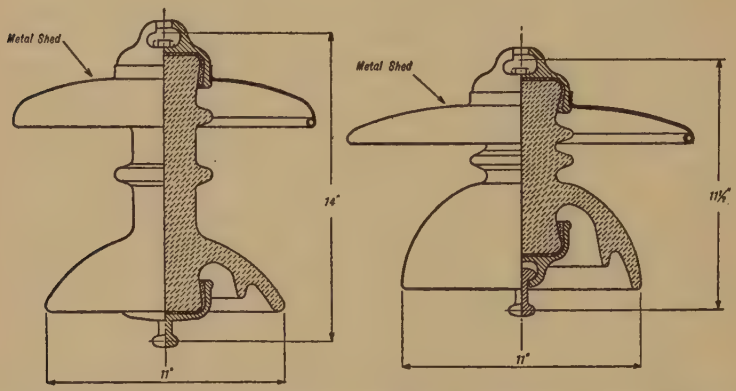


FIG. 26.—Standard and foreshortened model of Continental "Motor" insulator with metal shield.

portional to the number of units. In selecting the assembly for given line conditions it will be necessary to maintain a safety factor so that the operating voltage will not exceed a percentage of from 15 to 40 of the wet flashover. In some conditions a higher ratio is necessary.

The varying values of safety factor are based on the fact that lightning voltage will present relatively greater hazard to the line with low voltage insulators.

TABLE 23.—*Electrical Properties of Suspension Insulators (Standard 10-Inch Metal Cap Units).*

Number of units.	Dry flashover kilovolts.	Wet flashover kilovolts.	Safety factor.	Operating line kilovolts.
1	90	60	—	—
2	160	100	4½	22
3	215	140	4¼	33
4	265	180	3½	50
5	315	220	3½	66
6	355	260	3	88
7	385	300	3	100
8	410	340	3	110
9	425	380	3	132
10	435	420	2¾	154

At the higher voltages the distribution of potential across the insulator units becomes less uniform, and in a 10-unit string instead of each disc carrying 10 per cent. of the total drop the line unit may have as much as 30 per cent., however many units

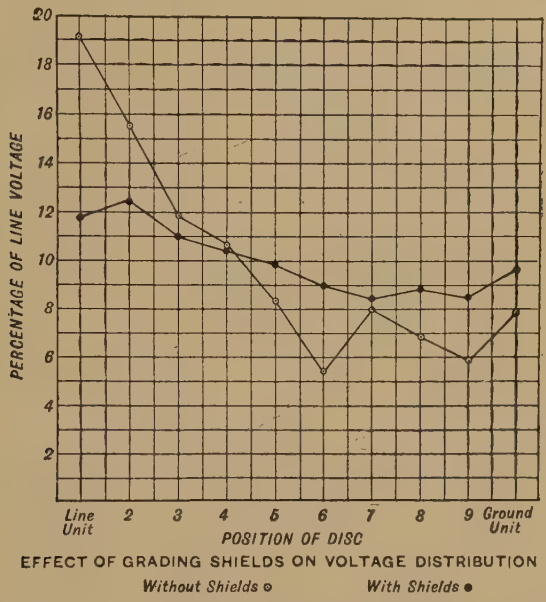


FIG. 27.—Experimental results by Dr. H. J. Ryan, showing the effect of shield rings on an insulator string.

may be added. This embarrassing condition is due to the varying capacitance to ground throughout the string. To render the distribution more uniform, a metal shield or ring has been adopted which surrounds the lower unit and equalizes the various capacities to ground. Such metallic shield rings of cast iron or aluminum are now becoming a regular feature in the design of transmission lines operating at more than 150 kilovolts, and by the distribution they afford, make it possible to secure reasonably safe operation with the minimum number of insulator units per string.

Reducing the high voltage across the line unit will elminate local corona discharge at this point, and at the same time avert

many troubles which arise therefrom. On the other hand, the shield ring will encourage flashover, but as it forms a protection to the insulators the arc need not be destructive.

TABLE 24.—*Voltage Distribution on a 10-Unit Insulator Assembly.* (*Professor H. J. Ryan*).

Unit number (from line).	Percentage of total voltage. Unshielded.	With shield ring.
1	19.0	11.8
2	15.5	12.4
3	12.0	11.0
4	10.5	10.4
5	8.3	9.8
6	5.5	9.0
7	8.0	8.5
8	7.0	8.9
9	6.0	8.5
10	8.0	9.6

An alternative to the shield ring lies in the adoption of graded insulator discs a notable installation of which is to be found on the 220 kilovolt transmission system of the Pacific Gas and Electric Company. Three different forms of disc are employed in each string together with a spun copper shield covering the bottom unit in a manner similar to that just described. The obvious criticism to this arrangement is that the necessity for carrying replacement stocks of three different types of unit is troublesome and costly. Other grading arrangements have adopted some form of detachable metal cap an appropriate size of which could be applied to every insulator in the assembly in order to modify its capacity to earth and so equalize the charging current and the voltage drop throughout the string. This device has proved unsatisfactory because the loose metal discs did not have quite the effect desired and furthermore they were found to lead to bad cascading in the case of a flashover.

The foregoing brief summary will assist in the selection of the minimum number of discs for a given service under normal conditions. For high altitudes, industrial districts with soot and dust deposits, or in the regions of salt fogs, one or more

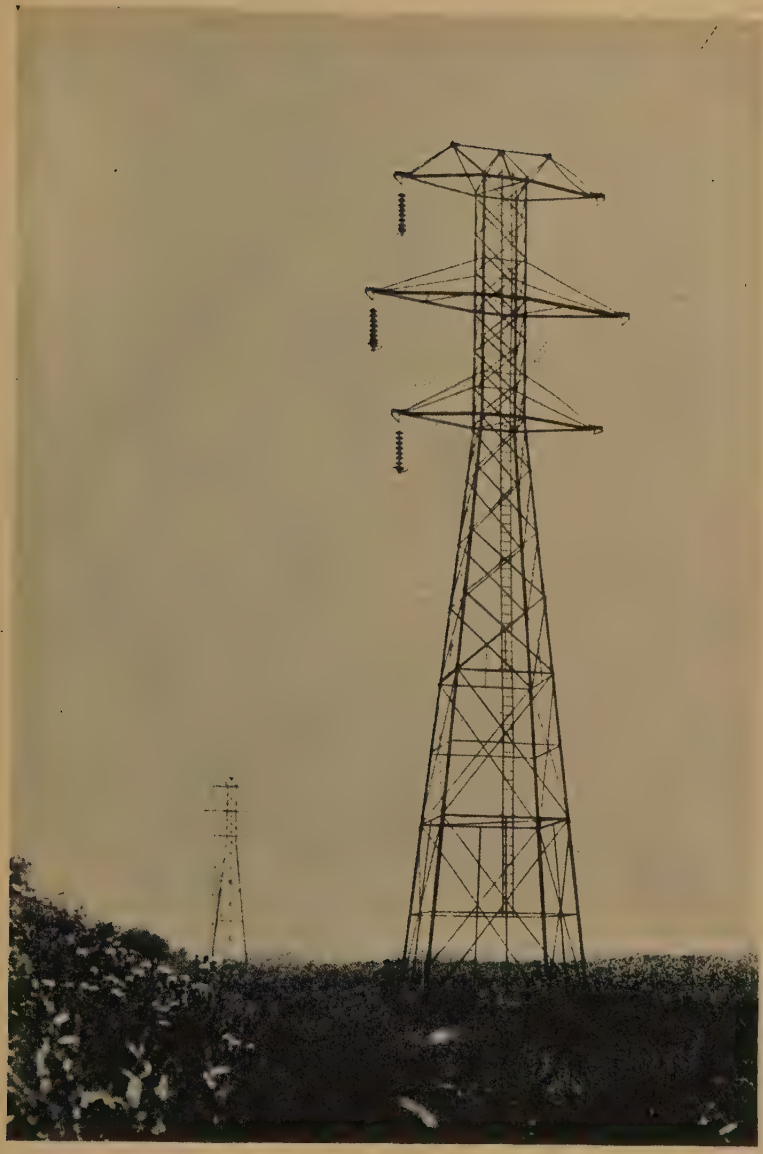


FIG. 28.—SHIELD RINGS AND INSULATOR LINKS AS USED ON A 132-KILOVOLT LINE IN ILLINOIS.

[*Facing page 86.*

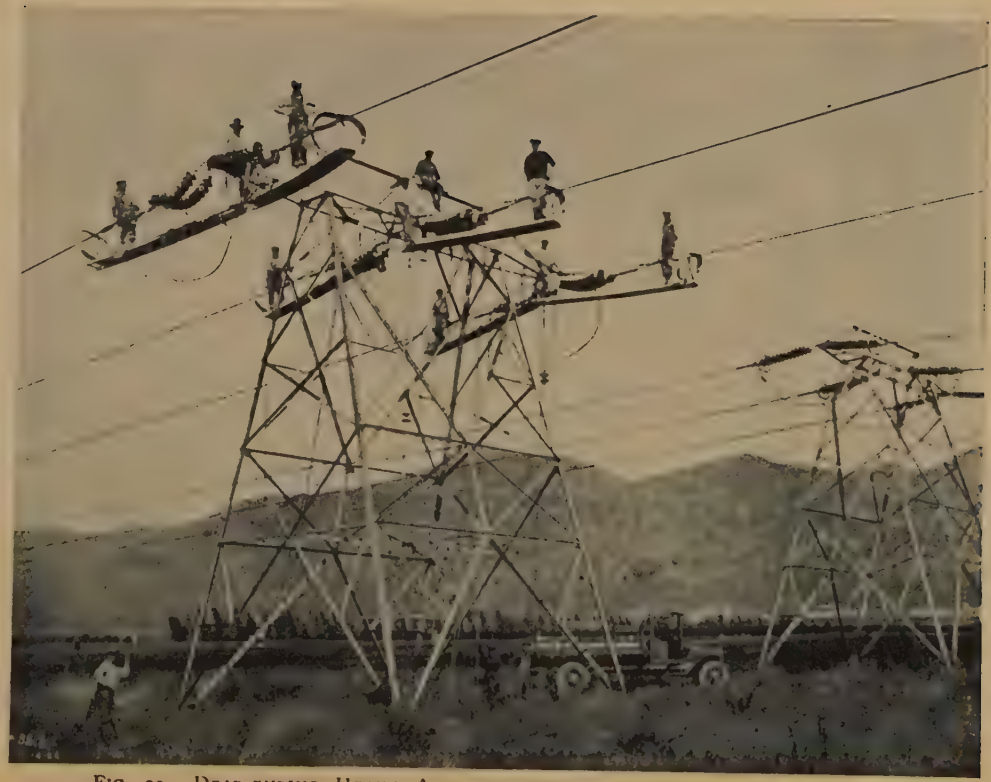


FIG. 29.—DEAD-ENDING HEAVY ALUMINUM-STEEL CONDUCTORS AND INSTALLING INSULATORS FOR 220 KILOVOLTS. [*Facing page 87.*

extra units should be added to the string, and the same applies for strain positions.

Strain Insulators.—Although the suspension insulator normally carries only the weight of the wire and its superimposed loading, if any, there are certain points in the line where the wire is anchored and its entire tension is taken up. Here the duty on the insulators is very severe, and this fact leads to more rapid deterioration at such points.

As commonly employed, the strain insulator is simply a suspension unit set on edge. It is therefore little more than a makeshift, and it is not surprising to note a depreciation of such units of approximately ten times that obtaining in a suspended position. It is not a little remarkable that the manufacturers have shown so little desire to develop a design especially for strain positions.

The ideal strain insulator will maintain the porcelain in compression; it will use no cement and will be designed so that failure will not let the line down, even though it be grounded. If a mechanical failure occurs at a dead-end point so that the insulator parts, the wire will probably be released; severe shocks will be carried to several of the nearby insulators and towers in both directions of the line, possibly breaking insulators, bending crossarms and burning off the wire in a number of places. Mechanical stability is therefore paramount, even if the unit should fail electrically.

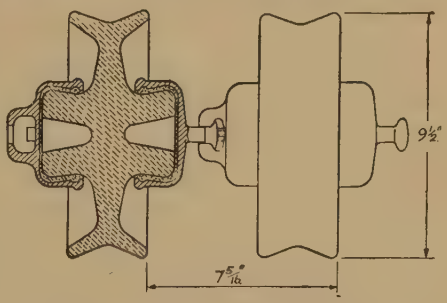


FIG. 30.—Continental "double cap" type of strain insulator with caps leaded on.

Manufacturers of metal cap type insulators as already indicated are producing a "high strength" unit, which is a heavier form of the conventional suspension disc, but is intended for strain positions. It may be expected to show an ultimate

strength of 20,000 lb. or even higher as compared with 9,000 lb. for the suspension type, but as electrical failure will generally take place when the unit is stressed to about 80 per cent. of these figures, the practical limit is nearer 16,000 and 7,200 respectively. The extra strength in the special unit is derived from the use of a longer stud and cemented portion, and not from any new departure in design. The tendency in modern line practice is to relieve the dead ends from stress as far as possible, and by reducing the number of strain insulators to the minimum, as well as by yoking two or more strings in parallel at points of heavy strain, the present commercial designs are found to be reasonably adequate.

As an illustration of the type of load to be carried, a stranded copper conductor of 500,000 cir. mils (0.40 square inch) may be considered. This is in no way an unusual size of conductor, and, as commonly strung, would have a maximum working tension of about 10,000 lb. Wherever an anchor point may be, the full tension of the cable would have to be taken up, and, as the maximum safe load on an insulator string is about 3,000 lb., a quadruple yoke would be necessary, incorporating four strings, each of probably 8 or 10 units. With high-strength insulators one half the number of strings would be necessary.

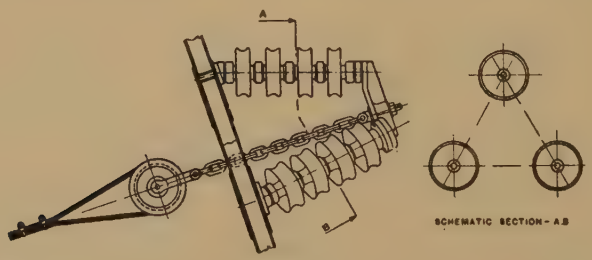


FIG. 31.—Pedestal type insulator assembly for a long span, showing the use of a sheave for anchoring the conductor.

On certain long-span crossings where steel or composite conductors are used the tension may be still greater, as, for instance, a remarkable crossing of the Little Tennessee River, in Ten-

nessee (see p. 214). Aluminum-steel conductors are used with a normal tension of 30,000 lb. and a maximum figure of probably 50 per cent. higher, the span being nearly a mile between supports. This strain is carried by a group of eight insulators, equalized and connected to the cable through a spring. Under maximum loading each string therefore carries some 6,000 lb., corresponding to a safety factor of three on the string of special high-strength discs. For similar situations an oil-filled wood stick insulator has been used. In such a unit the tension is carried by one or two straight cylindrical rods of hickory, which is a very hard and uniform wood. These sticks are solidly coupled to yokes at their extremities and surrounded by a porcelain bushing which is hermetically sealed and filled with oil, being similar to a transformer or outlet bushing. Such a unit is made for a maximum working tension of 40,000 lb. and for voltages up to 150 kilovolts, but experience would show that this type is not yet developed to the maximum reliability, and it has not replaced the multiple yoke of standard insulator assemblies for any significant installations.

TABLE 25.—*Strain Insulator Assemblies.*

System.	Number of strings.	Units per string.	Maximum tension.	Tension per string.	Equalization.
Mississippi River Power Co., Missouri..	6	8	24,000	4,000	Levers
Great Western Power Co., California...	8	15	20,000	2,500	Springs
Knoxville Power Co., Tennessee.....	8	12	30,000	3,750	Spring
Southern California Edison, California..	2	8	12,000	6,000	Yoke

Probably in the near future the interlinked type of unit will be produced in a form suitable for use in extra high-strain positions, as there is clearly no finality represented by the strain insulators at present in use. In a paper before the International High Tension Conference in 1923, R. P. Jackson says:

> "The Great Western Power Co., at the crossing of Carquinez Straits, California, used fifteen unit discs in series, and the stress is about equalized on all the strings

by means of helical compression springs. In some cases such multiple strings are equalized in pairs with a yoke, and the various pairs in turn yoked in pairs. This avoids the use of springs, and should give accurate balancing, but involves increased length and weight of the total insulating assembly. Although effective and built up of standard insulator units, yet the whole assembly, with the hundred and twenty separate insulators, impresses one as in a sense a monstrosity. It would seem that high-strength insulator units must be forthcoming which will at least reduce the multiplicity of pieces."

A new and remarkable design of strain insulator has been introduced by an American manufacturer, and may be found to

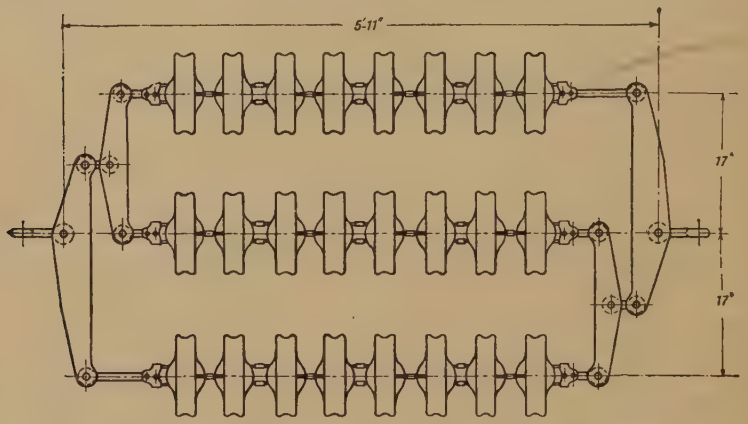


FIG. 32.—Equalizing insulator yoke for heavy strain positions.

satisfy the most rigid requirements for heavy strain positions. No cement is used in the assembly, and the porcelain is entirely in compression. The porcelain element is in the form of a hollow cylinder or, more properly, a cone frustrum, as it has a slight taper. If a steel rod be passed through the cylinder connected to a grip at one end, and a steel shell surround the exterior of the assembly holding the porcelain at the other end, it is obvious that the unit is in pure compression, and as the rod makes no contact with the shell, the space between them repre-

sents the flashover distance. This is somewhat limited in a single unit, but it is stated that an electrical flashover of 130 kilovolts can be withstood, in which case an assembly of three or four units would suffice for the highest voltage in commercial operation. The great multiplicity of parts above referred to is entirely avoided, and the operating hazard correspondingly reduced. In mechanical load this strain insulator will carry up to 400,000 lb. without electrical failure. (Fig. 33.)

Very long spans offer another problem which is difficult to solve. The effect of wind is to set up a series of harmonic ripples in the wire which, under certain conditions, may culminate in a mechanical surge, but in any event the constant vibration is imposed upon the insulators, and tends to the demoralization of cement and porcelain. An adjustable tension device is combined with helical springs to damp out the vibrations, but is only partially successful. A tendency is at work to relieve the insulators of the tension of the span wire in these long crossings. As an illustration of this, the crossing of the St. Lawrence at Three Rivers, Quebec, is effected by steel cables, which are anchored to the towers, but not insulated. From the steel cable the aluminum conductor is suspended by a series of standard insulators at 400-foot intervals. Although this device was adopted as a makeshift in the year 1918, it has proved so satisfactory that it has since been maintained, and the advantages of relieving the insulator porcelain from excessive mechanical strain are so great as to warrant this practice being duplicated.

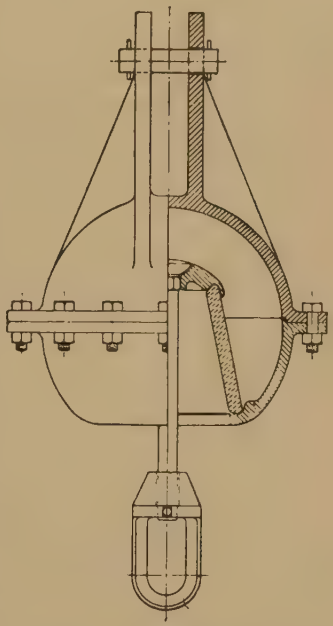


FIG. 33.—Special type of high strength strain insulator having porcelain element in compression (J. S. Lapp).

Under normal conditions suspension insulators hang vertically from the crossarm, and perpendicular to the conductors which they support. No part of the tension in the wire is, therefore, normally carried by the insulator, its load consisting of the weight of half a span of wire on either side of the tower in addition to the weight of the insulator itself, together with clamps and superincumbent loading. The total will not generally exceed 1,000 lb. On the other hand, unequal adjacent spans will lead to unbalanced tension with changing temperature, and the insulator will swing in one or other direction. If the difference is likely to be appreciable, a semi-anchor insulator assembly may be installed; in the conventional design this consists of two strings hung in an "A" formation to take up a position intermediate between a strain and a suspension assembly, *i.e.*, at 45 degress to the direction of the wire. In such a device the swing of the insulators is limited, and each string carries approximately half the tension of the line wire at all times. In some quarters this is not believed advisable, and a vertical string of extra-strength units is used in place of the "A" disposition; in such a case sufficient weight should be applied to the insulator clamp to minimize swing.

Although it is desired to confine the present study to mechanical elements, it should be mentioned that the electrical design of insulators is now generally being approached from a new angle: The problem is no longer viewed as one of interposing a certain thickness of dielectric between line and ground, such thickness being calculated from the known puncture value and the safety factor. The use of the static shield ring has done much to show that certain external modifications may radically alter the duties and the efficacy of a given insulator. If it be supposed that an electrostatic field surrounds every conductor, it will be seen that the tendency of the lines of force is to become more and more bunched as the conductor becomes smaller. On the other hand, if the conductor be expanded out to form an equipotential surface, the field will also be liberally distributed. The phenomena of corona and of the flashover which often succeeds corona

are dependent not simply upon the difference of potential between two points, but to a great degree upon the density of the electrostatic field between them. A metal shield, carefully shaped and connected to one end of the insulator, will provide an equipotential surface which will distribute the field, and if properly proportioned it will be found to diminish the flashover distance for which the insulator is designed. Moreover, it will eliminate the necessity for shells of varying diameter. Such a principle is employed in the experimental insulator shown in the drawing (Fig. 34), where the insulating element is simply a hardwood stick. At the lower end, and concentric with it, is a spun copper ring formed of 6-inch tube and having a formed diameter of 17 inches outside. At the upper or ground end of the rod is a wide-spreading dished metal shield 45 inches in diameter. The overall length of the complete unit as designed for 110-volt operation is only 38½ inches. The design provides not merely for the distribution of the field, but, as far as possible, for placing the actual dielectric in the zone of minimum density. Electrical breakdown will, therefore, ultimately occur, not in the insulating element, but somewhere in the surrounding field. The heating and molecular demoralization of the dielectric, which are generally supposed to precede breakdown, are therefore obviated. Whilst this insulator is only in the experimental state, being developed by Dr. H. B. Smith, of Worcester Polytechnic Institute, U. S. A., it is believed to possess distinct commercial possibilities.

The value of the metal shield is also recognized in the design of the Swiss "Motor" type of insulator which is illustrated. (Fig. 26.) The body of the unit is of porcelain in a cylindrical form, with only one shell, to minimize leakage. Instead of the conventional cap and pin, a metal cap is leaded on at either end, that at the top being connected to the wide copper shield. The wet flashover voltage is considerably higher than with the conventional unit, so that an operating voltage of 25 to 30 kilovolts per element is usual.

According to the manufacturers this type of insulator (which carries the trade name "Motor" has the following characteristics. Its considerable length gives a flashover of about double that of a standard suspension unit while puncture in air is

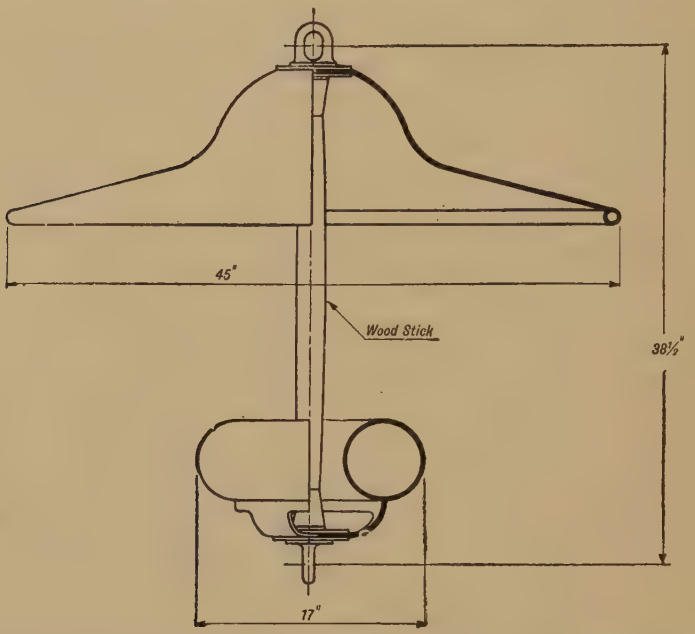


FIG. 34.—Experimental 110-kilovolt strain insulator with uniform dielectric field (Dr. H. B. Smith).

virtually unknown. A lead alloy is used in place of cement, forming a malleable cushion under each cap. The metal shed protects against rain and also shields the porcelain from destructive arcing and distributes the electric field. The porcelain is entirely in tension, simplifying calculations of strength. The approximate length of the porcelain cylinder is twelve inches in the standard insulator and the diameter three inches. Area of porcelain is therefore seven square inches and with a tensile strength of 2,000 lbs. sq. inch the ultimate strength of the insulator in tension will be 14,000 lb. which is somewhat in excess of the normal type of metal cap unit, although of

course inferior to the modern type of high strength unit. In respect of flashover characteristics the following figures are quoted:

TABLE 26.—*Flashover Values of "Motor" Insulator.*

No. of units.	Dry flashover, kv.	Wet flashover, kv.
1	133	100
2	268	188
3	376	272
4	500	320

Puncture test under oil, 335 kv.

As commonly installed, one unit is used for operation at 60 kilovolts with two in strain positions. For 88 kilovolts two units are used throughout.

Links and Weights.—A number of mechanical problems arise from the flexible character of the suspension insulator. It was

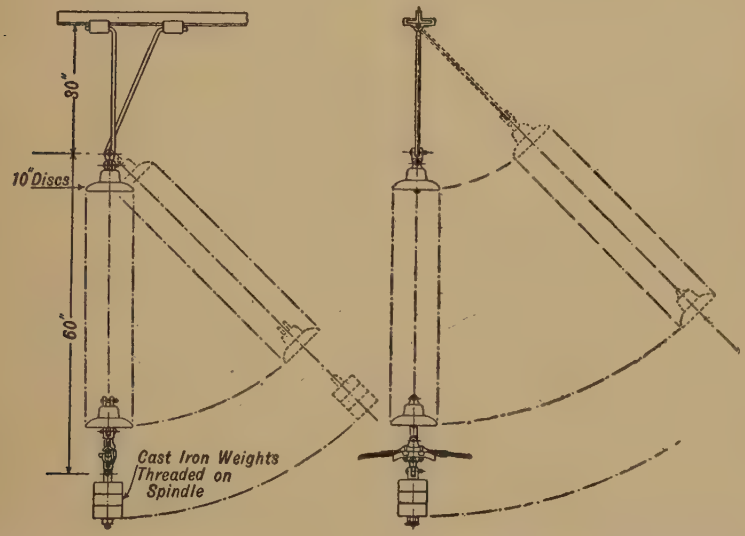


FIG. 35.—Use of insulator extension link to give maximum swing along the line and limited swing toward the tower.

just stated (p. 92) that a slightly unbalanced tension in the wires will pull the insulator out of the vertical. As the load on

the insulator is proportional to the cosine of the angle which it makes with the line wire, it is desirable to keep this angle as nearly as possible 90 degrees, especially with modern heavy conductors strung with a high mechanical tension. This is effected by adding to the length of the insulator a link or bracket which is free to swing from the crossarm. Thus, without affecting the linear movement of the wires, the insulator is maintained more nearly perpendicular, even under extreme conditions. Another advantage lies in the fact that, when a wire breaks, the shock which is thrown on the crossarm will be less if the insulator strings be long, and the length of link can be chosen with this in mind.

For modern high-tension transmission lines the insulator string is of the order of 5 to 6 feet long; it is not unusual to add to this a swinging bracket of 3 to 4 feet. The use of links will, however, have more scope on lines of lower voltage, where the insulator is necessarily shorter. Future increase of operating voltage can then be taken care of by simply substituting extra units for the link without any other change in design.

An important function of the link which has not been mentioned is the manner in which it amplifies the clearance. Where an insulator string supports the conductor five feet below the crossarm the clearance will of course only be maintained as long as the insulator hangs vertically. If it should swing 45°, which is not unusual in a heavy wind, the clearance is at once impaired as the conductor now hangs only three and a half feet below the crossarm. If a link is employed its length can, of course, be added to the clearance because it is hinged so as always to hang perpendicularly across the line although it may swing in the direction of the conductor. Links are particularly useful for installation on the outer arms of an angle tower because by holding the conductor at a sufficient distance from the crossarm and tower structure they often obviate the use of strain insulators. (Fig. 35.)

Another device which has a similar function is the insulator weight which is sometimes suspended below the conductor

clamp. Not only will such a weight limit the swing, but it will also resist uplift. In a mountainous country, where towers are at widely different elevations, the insulator on the lower of two towers may at times be subjected to a distinct pull-up. This is sometimes counteracted by tying down to a lower crossarm, but, where practicable, a cast iron weight of from 50 to 1,000 lb. will be mechanically superior, because it does not destroy the flexible characteristics of the line. Owing to the rapid deterioration of tie-down insulators, they have been removed from several installations and another device substituted.

As the art of transmission engineering is developed, the size and weight of conductor, length of insulator, and span distance all become increasingly greater. At the same time, mature experience indicates that every strain or dead-end point is a source of hazard; such points are, therefore, reduced to the minimum. The ballistic character of the line then becomes of the greatest mechanical value in taking up sudden and heavy loads without transmitting them immediately to the points of support; insulators will swing over from one span to the next, throwing a short additional length of wire into the section most heavily loaded, and so relieving the stress. Control of this movement is desirable, and the weighted insulator provides the best means of securing control. Another form of swinging offers greater hazard, that is, the lateral inclination of the insulator towards the support on an angle or under heavy wind loading. This effect can also be corrected by ballasting in the same way as described. Weights generally consist of cast iron discs 10 inches diameter and 2½ inches thick; they are drilled and assembled on a spindle, the appropriate number of units being threaded on for each location. Where the design calls for a large assembly, special clearances must be provided. Generally, however, the limited swing of a ballasted insulator makes it possible to use a tower with shorter crossarms.

Another fitting, which has a certain limited use for various reasons, is a form of shield or cover plate of sheet steel somewhat larger in diameter than the insulator, and which covers the

top unit of the string like an umbrella. For some time past these shields have been used on certain locations on the Inawashiro Co.'s 110-kilovolt transmission line in Japan. It was found that the topmost units showed a higher percentage of failures than any other, and this was ascribed partially to the

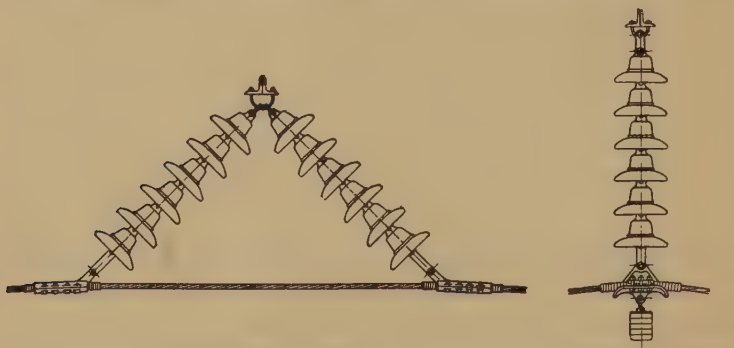


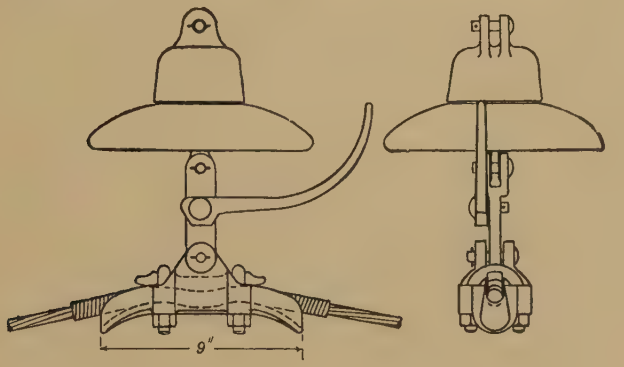
FIG. 36.—Alternative insulator assemblies for a semi-anchor position.

severe temperature changes arising out of a rainstorm on a hot day, as well as to troubles originating with birds roosting on the crossarm. This latter trouble is very prevalent in desert country, and certain sections of the 220-kilovolt lines of the Southern California Edison Co. are also equipped with "bird shields" above the topmost unit. These shields, in the form of a sheet steel pan, prevent any organic matter from falling on the units, and so initiating an arc over.

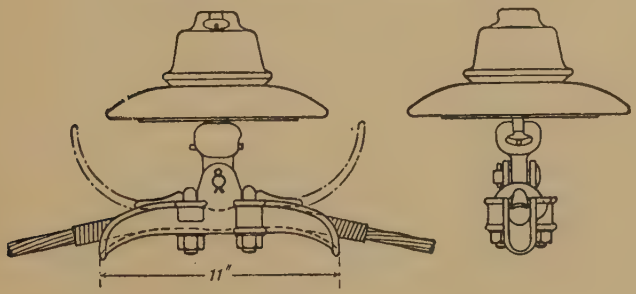
Another form of shield is used on the 165-kilovolt line of the City of Seattle, but in this case it is located below the bottom unit of the string, and immediately above the conductor. This device assists the distribution of the electrostatic field, reducing local corona, and is also stated to act as a splash plate during rain, wetting the under side of the lowermost unit, and so reducing its electric stress.

Hardware and Clamps.—By hardware is meant the metal fittings which form an integral part of the insulator unit, such as the cap and pin, whilst the clamps are detachable and have

the function of attaching the conductor. Malleable iron is usual for the caps, and for the pins mild steel is used. A drop-forged steel cap is now coming into wider use, however. All parts are hot galvanized, though where cost will not be an object sherardizing is a preferable process, yielding a distinct penetration of zinc. Two forms of connection are alternatively used for metal cap suspension insulators, the ball socket and the clevis, the former, of course, being the most flexible in every



SUSPENSION & SEMI-TENSION CLAMP



STANDARD SUSPENSION CLAMP

FIG. 37.—Two forms of insulator clamp.

direction. Where the clevis type is used, a cotter bolt of vanadium or other high-strength steel will probably be employed, because the entire load on the insulator is represented by the shear on the bolt.

At the upper end of the string is the eye attaching the insula-

tors to the crossarm, and in several recent installations this eye is designed of strictly limited ultimate strength, somewhat below that of the insulators or the distorting load of the crossarm. A sudden load exceeding all the design limits would, therefore, break this eye, but would not bend the crossarm or break the insultators; the damage could, therefore, be quickly repaired. Clamps for holding the conductor wire are virtually confined in their use to suspension insulators; as already mentioned, pin insulator clamps are not recommended. The suspension clamp should be a drop-forging or stamping, and it is made in two forms, for suspension and semi-anchor points respectively. The former is provided with two hook bolts, and the friction is limited, so that in the event of an abnormal load, as described, the wire may be expected to pull through the clamp. Tests have been made which showed that the conductor pulled through under a load of 3,000 to 3,500 lb., though the ultimate strength of the cable as well as of the insultators was more than double this. These facts are not to be taken to indicate that a broken wire or other emergency load is an everyday matter, because it is a very unusual contingency. Design has to be so ordered that, if ever the contingency arises, the damage done must be trivial; in effect, such a device as a slipping clamp or a breakable eye is analogous to a fusible boiler plug.

Anchor clamps are in a different class. Whatever happens, the wire must not slip at the anchor or dead-end point, and several designs of clamps are illustrated which ensure this. A curved seat is favored for dead-ending, as this increases the friction. In the case of a composite aluminum-steel cable of appreciable size, it is more usual to " snub-off " the steel, so that even if the aluminum, by virtue of its lower yield point, were to stretch or flow, the steel core will be held up to its breaking limit.

Too little attention has, in the past, been directed to the design of anchor and dead-end clamps, and it has not been appreciated that increasing sizes of wire and cable call for radical changes in clamp design. With a single wire or a seven-strand

cable it is clear that the tension in the wire can be readily converted into the friction of the grip. Experiment is probably the best means of determining the necessary length of grip for a given tension, but the tests are easily made. With conductors of thirty-seven or sixty-one strands the case is different, however, and with the tension uniformly distributed throughout the section of the cable it is not easy to predict just what length of grip will be necessary to gather up the load in the interior layers and the core. Beyond a certain point pressure exerted on the envelope, by tightening up the clamp bolts, will simply deform the outer wires without transferring the friction to the core. It must also be conceded that a test in the conventional machine

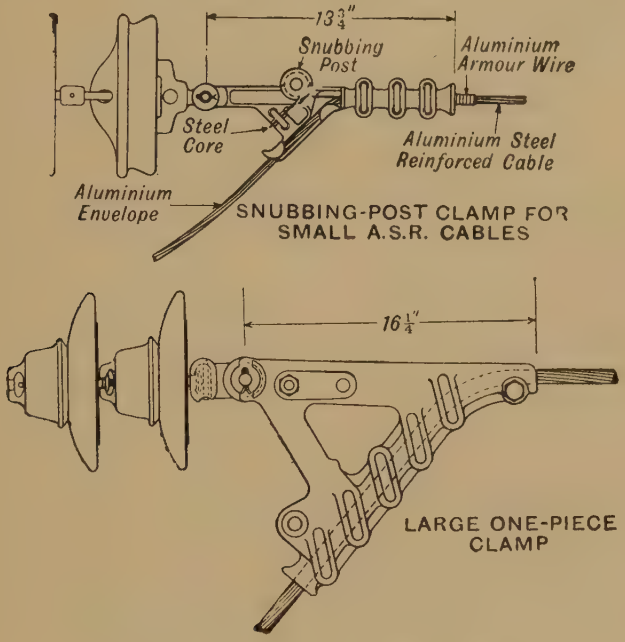


FIG. 38.—Two forms of anchor clamp.

has little value, because both the clamp under test and the testing machine grips make contact with the envelope of the cable. In the necessarily short length it is probable that very little of the load is carried by the core, so the tendency of the core wires to slip out of the grip is not tested at all.

For composite cables the problem is particularly acute, because the core will generally be under a heavier load than the envelope. The clamps on an important installation failed some years ago, due to the fact that whilst the dead-end clamps made excellent contact on the surface, they could not prevent slip of the core under heavy load. As the core slipped, the aluminum, by virtue of its greater ductility, extended, and the friction was still further reduced, and the effect became cumulative.

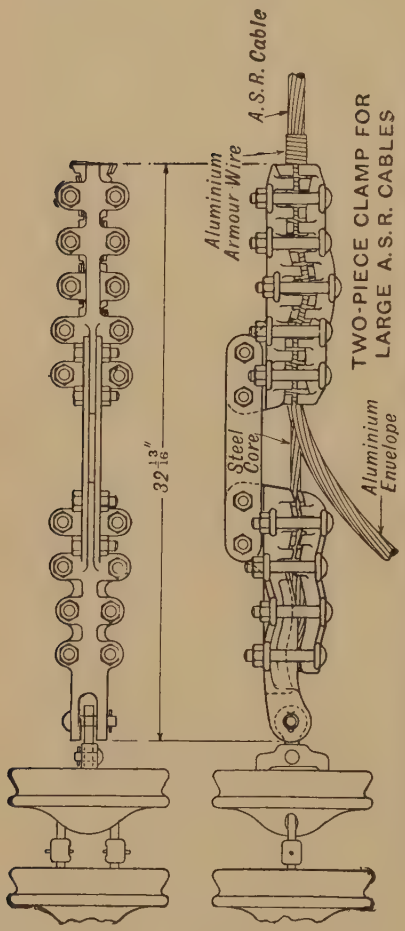


FIG. 39.—Standard form of anchor for clamping large aluminum-steel conductors.

For these reasons it will be seen that it is necessary in all composite cables to anchor the core separately, either by a snubbing post, around which the core wire is wound, or by means of an auxiliary clamp in tandem with the main clamp, the method, of course, depending upon the size of cable in question.

In one form of clamp which is employed for both simple and composite cables, the snubbing effect is carried out on the entire cable. This is done by bending the conductor around to an angle of about 50 degrees with the direction of the line, and clamping it in a waved seating. One of the merits of this design is that the core (where of galvanized steel) is not taken out and exposed, but remains in its normal position, surrounded by the

envelope. Destruction of the steel by rust is therefore precluded. This fact is of distinct importance, and on clamps where the steel wire is separately snubbed it is necessary to apply a coat of protective paint.

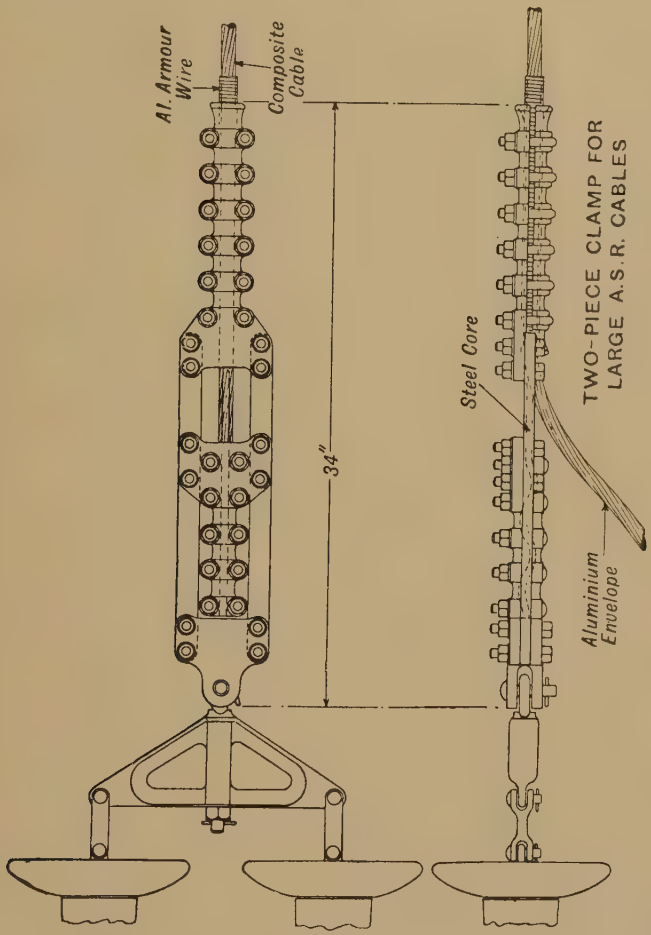


FIG. 40.—Special form of anchor clamp for large aluminum-steel conductors.

Most of the conductor clamps made up to the present have been in galvanized malleable iron, though in Germany there has been very considerable use of bronze for the purpose. Malleable iron is, without doubt, far too uncertain in its characteristics for use in a heavy anchor clamp, more especially

where it is held in tension. In one of the clamps illustrated (Fig. 40), the portion gripping the steel is designed to be in compression, so that the weight of the fitting is reduced and its factor of safety improved. Apart from this, the best practice is certainly to use cast steel for the entire clamp body. Notwithstanding its high cost, this practice is justified in the interests of safety.

In the design of clamps it must always be remembered that when a wire stretches under tension its diameter will be reduced. If this reduction is equal to the elastic deformation of the wire

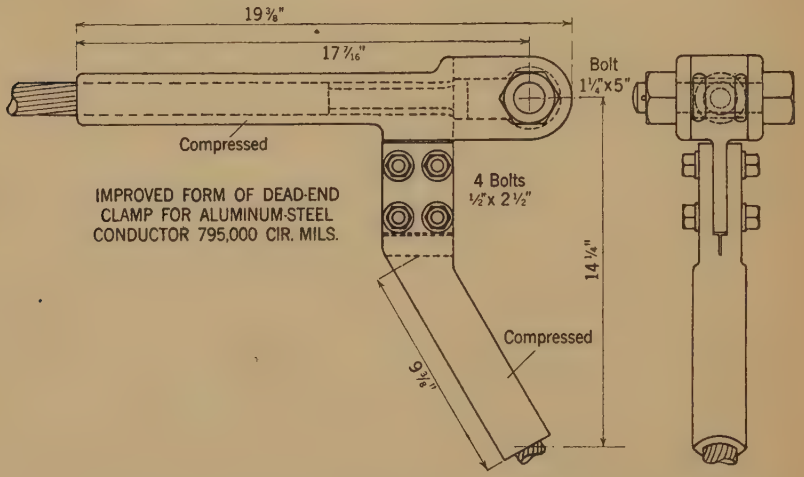


FIG. 41.—Compression type of dead-end clamp for aluminum-steel cable.

by the clamp, then the friction will disappear and the wire will slip. A liner or "shim" in the clamp corresponding to the material of the wire is of value in increasing friction. In many instances a serving of wire or metal tape is wrapped around the conductor before it is laid in the clamp, but such a wrapping limits the pressure of the clamp on the conductor. The best kind of liner is that which is pressed into the clamp in the factory, as it does not hinder the tightening of the clamp bolts.

One of the improvements now being applied to dead end clamps is the important matter of weight reduction. Where

conductors are drawn up to a high mechanical tension on a long span the wires will be almost continually in vibration and, as will be seen later, special precautions have to be taken to minimize the effects of this phenomenon. It is found that where the anchor clamp is very heavy the oscillations travelling along the conductor are very suddenly damped and there results a tendency for the wires to break just where they enter the clamp. As a result there has recently been developed for aluminum-steel cables a form of dead end clamp which consists of two concentric sleeves, one of soft steel and the other of aluminum. The core is anchored into the first by squeezing in the jaws of a portable hydraulic press after which the aluminum wires are laid up and similarly pressed into the aluminum sleeve. The aluminum body is provided with a clevis for attachment to the insulator as well as with a lug for connecting the jumper. (Fig. 41.)

Specifications and Tests.

Careful selection and testing of the insulators for a high tension line are of supreme importance, and there is now a general and uniform appreciation of this fact. In the manufacturers' works the following routine tests are usually applied:

(1) *Flashover.*—The shells are subjected to normal flashover voltage immediately after firing and before assembly. This is maintained for five minutes at the designed normal frequency.

(2) *Flashover.*—After assembly the dry flashover voltage is again applied for three minutes, any unit failing or cracking being rejected and any failures beyond a guaranteed maximum rejecting lot.

(3) *Puncture.*—Individual units which have passed the flashover test are tested for puncture in an oil tank. Uniformity of puncture voltage is required, the average variation (whether plus or minus) from a mean figure must not exceed 2 per cent.

(4) *Mechanical Test.*—A load equal to 40 per cent. of the rated ultimate strength of the unit is applied and maintained for three seconds. Subsequently the unit is tested electrically. For the ultimate strength test, 85 per cent. of the manufactur-

ers' rated load is applied. All units are allowed seven days, after cementing, before any mechanical test is made.

There is considerable difference of opinion on the testing of insulators, and in many quarters the above schedule is not thought sufficient. One insulator maker uses a high frequency test (200,000 cycles at 120 kilovolts) because the surges which contribute to insulator failure are generally of a high frequency order, and insulators are thus weeded out in the factory instead of failing afterwards on the line. Puncture test is also made at high frequency. A still more severe test is a simultaneous and combined 5,000 lb. tensile load with a 200,000-cycle flashover for two minutes.

An " overpotential " test is used by another manufacturer, in which the insulator is partially immersed in oil so that it cannot arc over. A voltage 20 per cent. higher than dry flashover is applied and held for two minutes.

The following specification of the engineers of the *Knoxville Power Co.* cover the insulators for a 150-kilovolt line:

> " Porcelain bodies to be non-absorbent, thoroughly vitrified, free from cracks, etc., and surfaces in contact with cement to be unglazed.
>
> " Caps to be galvanized malleable iron of minimum ultimate strength of 30,000 lb. per square inch and designed for a maximum stress of 12,000 lb. per square inch at 9,500 lb. total load.
>
> " Pins to be of soft steel drop forgings designed for a maximum stress of 35,000 lb. per square inch at 9,500 lb. total load.
>
> " Parts to be cemented together with slow-setting neat Portland cement of best quality.
>
> " Porcelain parts taken from kiln to be subjected to dry flashover test for five minutes. Five days after cementing, and before six days, units to be subjected to 3,500 lb. load for five minutes. Units to show puncture voltage under oil of at least 120 per cent. of dry flashover voltage.

Ultimate tensile strength of complete unit to be not less than 8,500 lb. Resistance of units to be infinite when tested with 1,000-volt 2,000-megohm megger. Standard A.I.E.E. wet flashover test for complete string of ten units to be not less than 390,000 volts at 60 cycles."

In the *American Institute of Electrical Engineers'* specification for suspension units the following are called for under the heading of Design Tests:

Dry Flashover.—The insulator or string is suspended vertically by the regular commercial hardware so that no part of the grounded structure is nearer than 3 feet or one and a half times the length of string to the unit or string. An inverted ¾ inch pipe tee is connected to the insulator pin in such a way that the distance from the pipe to the lowest edge of the porcelain shall not be more than 0.7 times the diameter of the lowest unit. The initial voltage to be applied is approximately 80 per cent. of the dry flashover and this is increased at the rate of ten kilovolts in 15 seconds until flashover occurs.

Wet Flashover.—With the same arrangement as above a finely divided and reasonably uniform shower of water is maintained on the unit at an angle of 45°. Rate of flow is to be 0.2 inch per minute and the specific resistance of the water used is required to be between the limits 6,000 to 8,000 ohms per inch cube. Pressure at the spray nozzle to be between 35 and 50 lb. per square inch. Methods of applying voltage are as above except that the water spray is started one minute before the voltage is applied.

Corona Voltage.—Using the same arrangement as for the dry flashover in a darkened room a voltage well above the corona point is applied and gradually lowered until all discharges disappear from the insulator. This point is defined as the corona voltage.

Puncture Voltage.—The insulator unit is inverted and immersed in oil the voltage being applied through the medium of the metal cap and stud or other appropriate hardware. The

dry flashover voltage is first applied and increased at the rate of one kilovolt per second until puncture occurs.

Mechanical and Electrical Test.—A voltage of a value equal to 75 per cent. of the dry flashover at not more than 60 cycles is applied and maintained on the insulator simultaneously with a mechanical load. This load is first applied at a value of about 75 per cent. of the assumed final value and then increased at the rate of 2,000 lb. per minute until puncture takes place.

A most practical and concise specification on high-tension insulators has recently been published by the *British Engineering Standards Association.* The terminology differentiates between "supporting" and "tensioning" units, the latter being designed to carry the entire maximum tension in the conductor. In either event the maximum load on the insulator shall not exceed 40 per cent. of its yield point. Provision is made that pin-type insulators shall not engage directly with a hard-metal screw thread.

The "type tests" or design tests include a dry flashover on units which have been heated in water at 50° C. for one hour, and immediately immersed in ice and water for a like period. This test is repeated three times on the same insulator. Flashover test is given by connecting a wire to the insulator exactly as in service and applying the test voltage (of 25 to 100 cycles) at the rate of 1 kilovolt per second until flashover occurs. For the wet test, water is sprayed at the rate of 1 inch in five minutes, being projected at 45 degrees on the units. The water temperature to be 15° C., and its resistance not more than 20,000 ohms per centimeter cube. Puncture test is made under oil in the usual manner.

For the mechanical test an ultimate load is specified, two and a half times the working load for all types of insulator. No provision is made, however, for any combined mechanical and flashover test, and there is some reason to believe such a test to be of value. In the case of the pin-type unit, the load is applied horizontally by means of a steel cable around the neck of the insulator, the latter being mounted on its pin. The suspension

or tension unit is tested by application of a direct tension to the cap and the stud.

In the case of the fuchsine test for porosity, which has already been referred to, the British Standard Specification requires the broken pieces of porcelain to be immersed for twenty-four hours in a 0.5 per cent. solution under a pressure of 2,000 lb. per square inch. This is ten times as high as is usual in American practice, but is believed to be necessary to ensure penetration.

For the routine tests as applied to the entire factory production, dry flashover voltage is applied and maintained for five minutes, the voltage being a sine wave, and the periodicity from 25 to 100. Every unit of the suspension and tension type is tested mechanically by applying 120 per cent. of the service load for one minute. The same test may be applied to 5 per cent. of the pin-type units in production.

CHAPTER III

SUPPORTS

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Choice of Supports.—In a broad sense, the selection of a supporting structure for a transmission line lies between wood and steel. All the early and lower-voltage lines were strung upon wood poles; virtually all the newer installations are built with steel structures. The conditions favoring the use of wood poles are accessibility of good timber and, to a lesser degree, a maximum operating voltage of 66,000 and a maximum power output of about 25,000 kva. per circuit. On the other hand, in districts where timber is scarce, steel construction may be more economical, even for the above conditions, and if the power transmitted be large, the argument in favor of steel will be greater.

While the timber pole has still a wide field in distribution practice its use for transmission line work has become very restricted due to two causes. In the first place selected poles whether of cedar or chestnut are becoming increasingly scarce especially in the larger sizes and their cost correspondingly high. In the second place, the development of power transmission systems has led to successively increasing voltage and power per

circuit, this being reflected in necessarily wide spacing of wires and in heavy conductors. To accommodate the long crossarms, twin poles have been adopted spaced ten to twelve feet apart and braced with the crossarm at the top. The stress of the heavy conductors has been taken up by using heavy poles, relatively short spans and guying the supports in four directions. It is obvious however, that this involves working very closely up against the physical limits of the subject and does not make for the best engineering. In referring to a 110 kilovolt wood pole line, Mr. L. J. Moore of the San Joaquin Light & Power Corporation makes the following statement:

> "From a standpoint of service it is no doubt true that a steel pole is the better. Its life is of course longer than that of the wood pole and if this is twice as long it naturally holds that the interruption to service for the changing of supports would be not over one half the number in the case of steel as of wood. However, in the particular instance herein described it is felt that the line as constructed is not large enough to handle the ultimate power transmission of the Company." *

Selection of a wood or steel support will therefore depend upon the capacity and the location of the line. In a timber country such as Washington, Oregon and the Sierras of California, the timber pole is the logical support unless the capacity of the line is of the order of 50,000 to 100,000 kva. per circuit, in which case it may be better practice to ship structural steel towers in from the mills possibly one thousand miles distant.

In Great Britain, where telegraph line work has been developed to a higher engineering plane than in most countries, the commercial creosoted wood pole is of a very high order of quality, and in its larger sizes is equally available for telegraph or power work. The heaviest conductors, with the conventional loading, can be carried by the braced "A" or, preferably,

* *Elec. World,* vol. 78, p. 614.

the " H " form of twin pole with an ample spacing distance for 110 kilovolts if necessary. The type of pole commercially available in Britain has been briefly indicated by Burkewood Welbourn in a recent paper: *

> " Most of the work already carried out has been done with winterfelled red fir poles creosoted by the Bethell process to the G.P.O. standard of an average of 10 lb. of creosote per cubic foot of timber. There is good reason to anticipate a life of thirty to fifty years if they are left undisturbed, and if they are erected within a few months after creosoting. The reason for this is that the free creosote drains into the earth around the poles and forms an additional germicide protection."

A further advantage of creosote treatment not mentioned above is that such poles are virtually fireproof. Experiments have been made in which a fire was deliberately built around the pole, but only superficial charring was the result. This fact presents the impregnated pole in a most favorable light in the possible event of a forest or brushwood fire, or of a broken-down insulator or flashover due to lightning. Rapid deterioration of timber has been the experience on many high-tension lines, due to leakage of relatively insignificant currents, which ultimately reduced the pole to matchwood. This would be taken into account in connection with the above estimated life of thirty-five or longer. With voltages of 50,000 or more the expectation of life is much less, unless the crossarm be grounded at each pole.

American poles, as commonly used, are distinctly inferior to British, for which reason American engineers have come to associate maximum reliability only with steel construction. By steel construction is generally meant a wide-base tower, usually a system of determinate trusses designed upon logical structural lines. In certain districts in the United States where rights of way are strictly limited lattice steel poles are used, which differ

* *Journal I. E. E.*, vol. 52, p. 183.

from the towers in having a base of only 1 or 2 instead of 20 or 30 feet square, and corner posts virtually parallel, connected by cross lacing. As a structure a lattice pole is indeterminate, and is heavier and mechanically inferior to the tower. In similar situations hollow concrete poles are also coming into favor (more especially, in Europe), but have not been in use long enough for generalization. Tubular steel poles have but a very limited field, and their use has not been generally successful, either singly or combined in a structure. Although a tube is theoretically the lighest section for a beam or column, it is both more difficult to connect to adjoining members and more liable to deterioration than the conventional angle section.

Wood Poles.—As regards the type of wood pole most in use for transmission and distribution service in the United States and Canada the following estimate will be found interesting.

TABLE 27.—*Types of Wood Pole in Use.*

Timber.	Percentage of total poles installed.
Western Red Cedar	51
Chestnut	28
Northern White Cedar	12
Pine and Fir	7
Cypress, Redwood, Etc.	2

Of the foregoing, chestnut poles in the large size have already become extremely scarce, while cedar is tending in the same direction. With the improved methods of creosote treatment now in vogue a much greater proportion of pine poles will undoubtedly come into use.

For the above varieties of pole timber the following are average values for maximum ultimate fibre stress in a seasoned condition but not treated.

TABLE 28.—*Ultimate Fiber Stress of Timber.*

Western Red Cedar	4,500 lb. sq. in.
Chestnut	5,000 " " "
Northern White Cedar	4,000 " " "
Pine	8,500 " " "
Cypress	5,600 " " "

Due to the varying natural taper poles of a given length and butt diameter may show wide variation in diameter at the top for which reason they are usually classified into Classes A, B, and C, according to stoutness. The poles in Class A being the heaviest are those best adapted to transmission line construction where available. The taper of Class A yellow pine poles is represented by the following figures which are abstracted from the specifications of the National Electric Light Association.

TABLE 29.—*Dimension of Creosoted Yellow Pine Poles, Class A.* (*N. E. L. A. Specification.*)

Length, feet.	Depth of setting, feet.	Circumference, inches.	
		Top.	5 ft. from butt.
30	5½	22	35
35	6	22	38
40	6	22	40
45	6½	24	42½
50	7	24	44½
55	7½	24	47
60	8	24	49
65	8½	24	51
70	9	24	53
75	9½	24	55
80	10	24	57
85	10½	24	59
90	11	24	61

Specifications are also available covering cedar and chestnut poles, but it is believed that the creosoted pine will sooner or later become the most important by reason of scarcity and cost of other varieties of timber.

The British Standard Specification arose out of the earlier Post Office standards, and, as already indicated, calls for winter-felled red fir poles (usually originating in Norway) impregnated under pressure with not less than 12 lb. creosote to the cubic foot, either by means of the "full cell" (Bethell) or "empty cell" (Rüping) process. The creosote is to be distilled from coal tar, and is specified as having a density between the limits 1.015 and 1.07 at 100° F., whilst the water content is not to exceed 3 per cent.

The British standard rules for impregnation are explicit in stating that the treatment need not involve the retention of the full 12 lb. of creosote per cubic foot, but only in its injection.

In America until recently little or no care was bestowed upon the preservation of poles, the practice being to use timber as would naturally yield a long life. Cedar, being impregnated by Nature as well as being plentiful and of suitable length, has been the favorite material in the northern and western States, whilst chestnut poles have been more widely used in the East. Owing partly to the present scarcity of chestnut, straight yellow pine is coming into extensive use as a substitute, but such poles must of necessity be treated more thoroughly. Treatment of cedar poles in the United States usually consists in immersing the butts in a tank of heavy creosote oil, which is kept at boiling temperature for twelve to twenty-four hours; afterwards the poles are hoisted out and the butts immersed in a similar tank of oil at atmospheric temperature. A vacuum is created in the cells of the timber by the change in temperature, and the cold oil is drawn in freely. In a few cases a solution of zinc chloride or other inorganic compound is used. To assist in penetration and so render the butt treatment more effective, it is becoming customary to perforate the butt of the pole with a scarifier. A series of steel points are arranged on a belt so that they will roll in contact with the pole, puncturing the sapwood to a depth of ½inch, the pitch of the perforations being ½ by ⅞ inch.

The specification issued by a very extensive group of power systems in the United States reads as follows:

> " It is not the purpose of this specification to stipulate definitely the method by which the poles furnished hereunder shall be butt treated. However, before any work is done, the method to be followed shall be stated by the contractor in writing, and must be acceptable to the purchaser.
>
> " The impregnation shall be accomplished by the open-tank process, but no pointed instrument for assisting the oil in penetrating the wood shall be used. At least 90

per cent. of the sapwood shall be impregnated with creosote, and the absorption per unit of the impregnated wood shall be such that not less than 24 lb. of oil per cubic foot will be retained. The temperature of the oil shall not exceed 110° C. (230° F.) at any time poles are in hot bath."

The general argument underlying the "open-tank" process is that the butt of the pole, at or about the ground level, is the first part to decay, and it is, therefore, not economical to impregnate the entire pole. Gains or slots cut for the crossarms are usually painted with hot creosote. Nevertheless, thorough impregnation even of the butt is seldom or never attained by the open-tank method, and with the growing cost of timber more effective methods of treating will assuredly be more widely adopted.

The Bethell pressure-vacuum system, adopted for the treatment of red fir and yellow pine poles, is inherently thorough. It is performed only on well-seasoned timber, which, after trimming and drilling, is loaded horizontally on cars and run into steel pressure tanks. The first treatment is with steam at a pressure of 20 lb. per square inch or more; this is condensed and exhausted together with the sap, and the creosote is drawn in by the vacuum thus created. Further creosote is injected by pumping, and finally drained off and the poles removed.

A more economical process is the Rüping, in which the air pressure in the tank is raised to 75 lb., distending the cells in the timber; cresote is then forced in at an excess pressure of about 150 lb. After the treatment, the pressure is reduced to atmospheric, when the wood cells will reject the excess oil and yet remain thoroughly impregnated. The Bethell and Rüping are illustrations of the "full-cell" and "empty-cell" methods of treatment repectively. Both methods are employed for the impregnation of British pole timber as well as being rapidly extended in the United States.

In calculating strength the pole is, of course, considered as a cantilever or a beam anchored at one end. The load is gen-

erally concentrated on one or two crossarms. In such a case the bending moment

$$M = \frac{SI}{C} \text{ (lb.-feet)}$$

where S = maximum fiber stress pounds per square inch,
I = moment of inertia of the section,
C = distance from neutral axis to plane of maximum fiber stress in inches.

As $I = \frac{\pi D^4}{64}$, and $C = \frac{D}{2}$ (inches)

the maximum transverse load is

$$W = \frac{\pi \times D^3}{32 \times H} \times S$$

H being the height of load above the ground line in inches, and the value of D, the diameter (in inches), being taken at or near the ground line, or alternatively at the point where the pole is just 50 per cent. thicker than at the point of load application, whichever is the smaller. Values of ultimate fiber stress are assumed as in Table 28.

The taper of the pole is seen to be important. For a single horizontal load applied near the top the following reasoning shows the location of the weakest section, *i.e.*, the point at which the pole will fail. This method is due to Mr. R. D. Coombs.

If y = distance of weakest section below load,
d = diameter of pole at load,
t = increase in diameter per inch length,
P = resultant load,

$$S = \frac{M}{I/C} = \frac{Py}{.098 \times (d + ty)^3}$$

$$\frac{dS}{dy} = \frac{.098(d + ty)^3 P - 3 \times .098 Pyt(d + ty)^2}{.098^2(d + ty)^6} = 0$$

$$(d + ty) - 3ty = 0$$

$$y = \frac{d}{2t}$$

If d_1 is the diameter of pole at a distance y below the load, then

$$t = \frac{d_1 - d}{y}$$

and

$$y = \frac{d}{2t} = \frac{dy}{2(d_1 - d)}$$

$$2(d_1 - d)y = dy$$

$$2d_1 = 3d$$

$$d_1 = \frac{3d}{2}$$

The diameter of the weakest section of the pole is therefore one and a half times the diameter in the plane of the load. This fact is useful as a check on poles having considerable taper but in most cases making full allowance for deterioration the weakest section of the pole will be found at the ground level and calculations of strength should be made on this basis.

For calculating the permissible load on a pole, the bending moments due to wind load on the conductor are resolved with the tension of one or more broken conductors, according to the specified design loading. The resultant constitutes the transverse load, from which the fiber stress at the ground line can be calculated. Wind load on the pole is, of course, included, being generally applied at the midpoint. Crushing load due to the weight of wires with ice, crossarms, insulators, and the pole itself, increases the compression loading, and must, therefore, be added to the foregoing result in determining the aggregate of loads leading to failure. In British practice a safety factor of three and one half is applied, based upon the ultimate stress. In America, practice varies, and whilst the National Electric Light Association and other bodies recommend a factor of four, the National Electric Safety Code uses a figure of two. Such safety factors are only mandatory in respect of crossings over railways or public highways.

A study of the life of cedar poles has been made by Page Golsan with reference to conditions in California. The average

rate of decay at the ground line involved a reduction in strength which averaged as follows:

TABLE 30.—*Life of Cedar Poles* (*Golsan*).

Age of poles. Years.	Percentage of original strength.
0	100
2	95
4	79
6	64
8	53
10	42
12	32
14	25

For untreated poles it is often assumed that the diameter at the ground line will be reduced by deterioration and decay to 80 per cent. of its new dimension, and strength is calculated on this reduced size. Compound poles of the "A" or "H" type are frequently used for high-tension lines, and the latter is generally to be preferred. According to Welbourn, the "A" pole is four and one half, and the "H" pole three and one quarter times as strong as a single pole. The "H" pole can, however be more easily assembled in the field; it permits of a mechanically superior anchoring of the crossarm, and it allows of a slight transverse flexibility. As against this, with the "A" poles there is a distinct tendency for the scarfed portion, where the two poles join, to rack loose, in which case the strength of the structure begins to be impaired. In any event, it is very difficult to obtain the theoretically superior strength in practice. According to tests reported by W. B. Woodhouse, the transverse strength of an "A" pole assembly is appreciably less than the figures quoted, owing to shifting of the earth foundation and distortion of the frame. The "H" pole arrangement is used on some of the most recent high-tension lines with operating potentials of 110 to 165 kilovolts, where no other form of pole would yield the requisite spacing. As commonly used in England, the "H" pole is braced by the use of tension rods. This would seem to be open to criticism, because the combina-

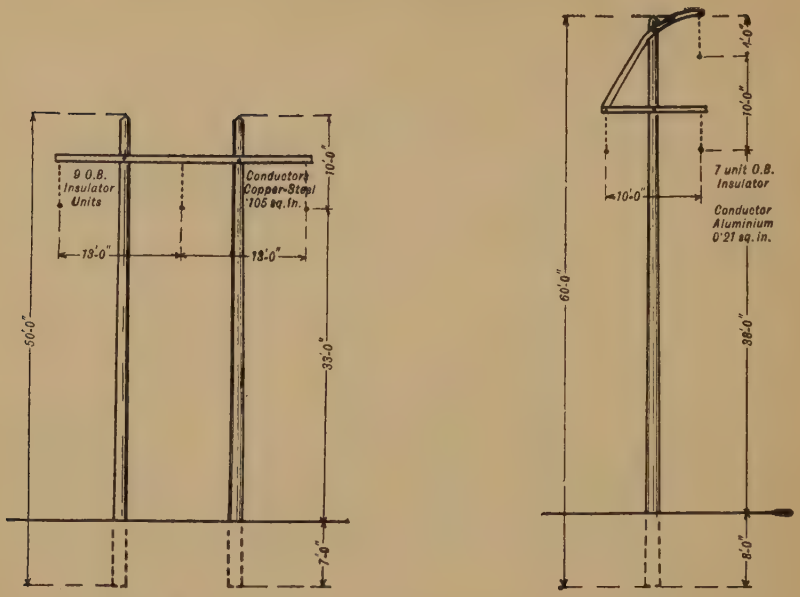

FIG. 42.—Wood poles for 100-kilovolt line construction. (Table 31.) A, Utah. Power Co.; B, San Joaquin Co.

tion of timber and metal in an assembly of this kind must be very carefully studied. Whilst the support is theoretically stronger than twin poles having a single crossarm near the top, the latter will stand very considerable deformation without harm, whereas in the reinforced design heavy shear loads will be imposed upon the compression pole.

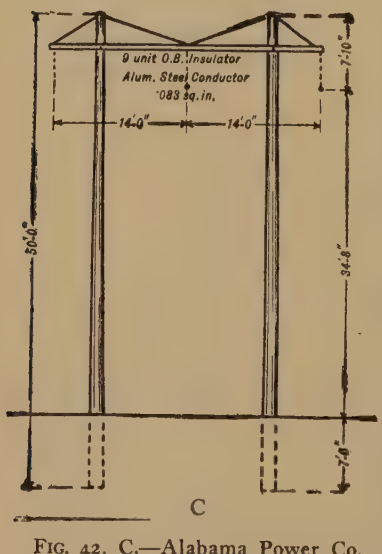

FIG. 42, C.—Alabama Power Co.

With all types of pole at present used guying is resorted to at frequent intervals, corner and dead-end strains being regularly cared for in this way to avoid an abnormally heavy pole structure. In some of the most recent

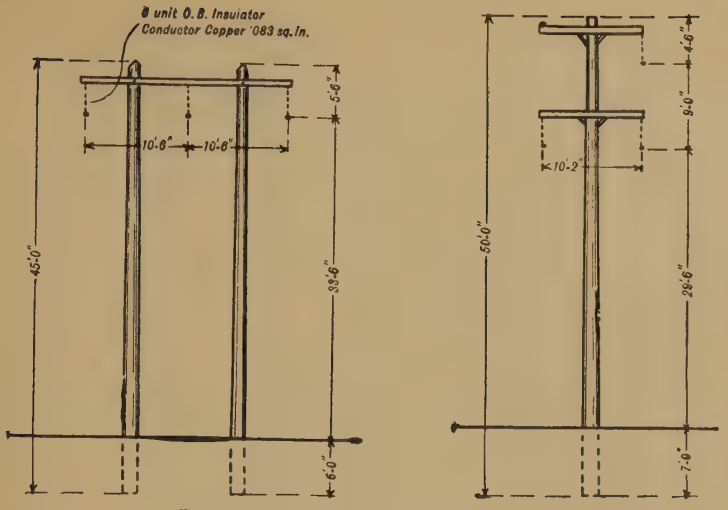

FIG. 42, D.—Montana Power Co.; E.—Chicago Milwaukee R.R.

pole lines every second support is guyed, the galvanized steel strand being carried out from a point near the crossarm at an angle of not less than 30 degrees, if practicable, and anchored to a " dead man " or log buried at least 6 feet underground. The matter of guying requires careful consideration when the line is planned and surveyed, because the width of right of way is greatly increased by the use of transverse guys, and this may in some cases make a steel support more economical simply by reason of the narrower right of way required. On the other hand, judiciously employed, guy wires will enable lighter poles to be used with undiminished reliability, and will materially help to reduce the cost of the line. The specifications of one very large power ultility in the United States refer to guy wires as follows:

> " Where the mechanical loads to be imposed upon the poles are greater than can be safely supported by the poles, additional strength shall be provided by the use of guys. This applies particularly to angles and dead ends, where the conductor stresses are sufficiently unbalanced to make guying necessary. The guy cable shall be 7/16-inch galvanized steel (stranded)."

A number of studies have been made on the subject of pole foundations, and it must be conceded that this forms a weak point in our knowledge of the art. There are so many variable factors, however, that it is questionable whether the resisting moments at the base of a pole can be satisfactorily evaluated. Probably owing to the great disparity in the ground encountered, empirical data may prove the most reliable. For ground varying in nature from loose sand to hard cinders the angle of repose is between 25 and 45 degrees, but thorough tamping will considerably modify these values, especially after the earth has had time to become set. A series of interesting tests has been briefly reported by E. B. Wedmore and W. B. Woodhouse to the International High Tension Conference (1923), in which poles of single " A " and " H " types were carefully set in loamy clay, which was thoroughly back-filled and tamped, the depth of setting being from 5 to 8 feet. The ground was allowed a period of ten weeks to consolidate, and a test made by applying a transverse horizontal load near the top of the pole. As a result, failure of the poles was found to be preceded by movement of the foundations, which naturally led to deformation of the frames and hastened the failure. Brace blocks were used to strengthen the compound poles below ground, but it is

TABLE 31.—*Wood Poles for 100-kilovolt Lines.* (Fig. 42.)

System.	Utah Power and Light Co.	San Joaquin Power Co.	Alabama Power Co.	Montana Power Co.	Chicago, Milwaukee, St. Paul R.R.
Kilovolts	130	110	110	100	100
Circuits	1	1	1	1	1
Type of pole	"H"	Single.	"H"	"H"	Single.
Material	Cedar.	Cedar.	Yellow pine.	Cedar.	Red cedar.
Crossarms	Fir.	Steel.	Yellow pine.	Fir.	Fir.
Spacing:					
Horizontal	13 ft.	10 ft.	13 ft.	10 ft. 6 in.	10 ft. 2 in.
Vertical	—	10 ft.	—	—	9 ft.
Conductors	Copper-steel.	Aluminum.	Copper.	Copper.	Copper-hemp.
Size	0.105	0.21	0.083	0.083	0.105
Ground wire	Steel.	None.	Steel.	Steel.	Steel.
Size	$2\frac{3}{8}$ in.	—	$\frac{3}{8}$ in.	$\frac{5}{16}$ in.	$\frac{3}{8}$ in.
Pole:					
Height (ft.)	55	60	50	45	50
Diameter (in.)	17	15	15	14	15
Span (ft.)	500	587	600	440	300–1,200

difficult to say whether their effect would be entirely beneficial. In American practice it is not usual to employ any such device except in unsound ground. Such framing makes the poles very difficult to set securely, and embarrasses the crew in back-filling and tamping. The ideal setting in sound earth is believed to be provided where the least disturbance is caused to the ground. This is secured by using a post-hole auger driven from the gear-box of a motor-truck, the diameter of the tool being exactly suited to the pole. If "A" or "H" poles are used, the spread of the legs should permit the two holes to be bored without mutual interference, and underground bracings should be omitted, whilst those above ground are best reduced to a minimum.

Steel Poles.—As already indicated, a tubular, lattice or expanded steel structure having a narrow base is termed a pole because it is considered to be simply under a bending load, and its truss system, if any, is indeterminate. Such steel poles are favored where the right-of-way is strictly limited in width, such as alongside a railway or highway. As with wood poles it is difficult to accommodate the very long modern crossarm on such a slender structure, consequently the voltage is limited as compared with a wide-base steel tower. Steel poles are usually heavier for a given loading. Of the various designs, that most in favor consists of four angle posts nearly parallel, connected by short lacing riveted to the main members. Such poles are, of course, fabricated in the shop and shipped complete or in sections 30 feet in length; they are invariably set in concrete foundations, because of the heavy horizontal reaction.

A novel form of steel truss pole has been devised by an important firm of structural engineers. It may be described as the conventional design with cross bracings and sides nearly parallel, but with the corner posts omitted. A brief examination will show that the device is structurally perfect. The shear loads are carried down to the foundations by the bracings just as effectively as if the design had corner posts, and with considerable economy in weight and cost.

Whilst narrow-base steel structures are seldom specified for heavy-line construction in America, they have attained considerable vogue in Europe. It is believed that the torsion load arising from a broken conductor at the end of a long crossarm is far better resisted by the wide-base tower, and certain failures of steel poles in Germany would appear to endorse this. Referring to Fig. 41, it is interesting to compare the American design of support with that used in Germany for a similar size of conductor. In each case it may be assumed that a conductor of approximately 0.20 square inch section is carried at each crossarm, and that the maximum tension on this wire, if of copper, will be of the order of 5,000 lb. In the case of a broken wire on the Pacific Gas and Electric Tower, the torsion load corresponding to a broken wire at the lower crossarm will be

$$5{,}000 \times \frac{9}{2.5} \times \frac{1}{4} = 4{,}500 \text{ lb.}$$

(where the radial length of crossarm is 9 feet, and the width of basket 5 feet).

For the German type of steel pole illustrated the torsion on one face will be

$$5{,}000 \times \frac{14.75}{1.75} \times \frac{1}{4} = 10{,}500 \text{ lb.}$$

To carry this load down to the base the web members must be relatively heavy, and in actuality the German steel pole is almost 30 per cent. heavier than the tower used by the Pacific Gas Co., whilst the latter probably has a greater safety factor against deformation. It is no doubt due to appreciation of these heavy torsion loads that German engineers have shown a tendency to adopt a swinging crossarm, which will yield with the broken wire and relieve the structure. This device will obviously bring a series of new problems into consideration.

Where a lattice steel pole line is necessitated by reason of narrow right-of-way, or from other causes, it will be found prudent to maintain the shortest possible crossarms, and, if necessary, to diminish the span length and the tension in the

wires. For pressures higher than 66 kilovolts it may be found necessary to use single-circuit structures rather than design for very long crossarms, with their consequent heavy torque on the narrow column. An example of a satisfactory design of narrow-base lattice steel pole is shown on the 66-kilovolt line of the Turlock Irrigation District, in California. These structures carry three crossarms for the double-circuit line, and are shop assembled, being riveted throughout with galvanized steel members. The main particulars are given in the following table:

TABLE 32.—*Lattice Poles for 66-kilovolt Line.*

Number of circuits	2
Capacity per circuit (kva.)	20,000
Area of conductor (sq. in.)	0.083
Span (ft.)	700
Total height of pole (ft.)	52½
Weight of steel (lb.)	1,844
Weight of concrete foundation	355
Test loads, breast pull	7,200
Test loads, torsion	4,300

For certain conditions, one of the most economical types of steel support is the expanded metal truss. This design has the merit of not being built of angle posts with crosslacing, but is fabricated in one piece from an I section in the manner described by the manufacturers, as follows:

> "The I section is first sheared through the web by a rotary shear, leaving intact portions at fixed intervals throughout the length of the section. The section is then heated in a continuous oil heating furnace to a temperature of about 1,400° F. The section is then charged into the expanding machine, which automatically grips the flanges throughout their entire length, and then expands the section to the desired dimensions while hot. Expanding the sheared web causes the middle portion of the web to take a zigzag form, and thus creates a series of triangles in alignment and produces a perfect one-piece steel truss."

It would be observed that the truss contains no rivets or bolts,

but is in one piece. The finished beam can be used singly as a pole or combined with others to form a built-up structure of greater strength. A definite taper is provided in fabrication, but, as the maximum length of a section is 35 feet, it is often necessary to splice together two lengths or otherwise combine them.

Concrete Poles.—A concrete pole forms a substitute for a wood pole, with the advantage that the former is designed specifically for the desired service, that it is symmetrical and sightly, and that it is composed of inorganic material, subject to little or no deterioration with time. Poles are cast either solid or hollow, being reinforced with steel rods in either case. The conventional solid pole is cast in a horizontal mould, the mixture used being 3 : 2 : 1, or richer, and well puddled. Wood blocks or pegs are inserted in the mould to form bolt holes where necessary. Slow setting is essential to a satisfactory product. Hollow poles have the merit of lighter weight for a given strength, and are more in favor in Europe, whereas most of the concrete poles in America are of the solid type. The hollow pole is best produced by a centrifugal method, the mould having no core, but being rapidly rotated whilst the mixture is setting.

The merits of the centrifugally moulded hollow pole have been indicated by J. Edwin Storr in a recent paper * by the statement:

> " Concrete poles can be built wonderfully flexible; 900 hollow poles 61 feet long were recently made for a Swedish contract. A test load of 6,750 lb. caused a deflection of 4 feet 6 inches without cracks or permanent deflection. When the load was increased to 7,600 lb., a deflection of 10 per cent. of the pole height was attained without breaking."

The installation referred to above is that of the State water-power system of Sweden, transmitting energy at 132 kilovolts from Trollhattan to Westeras. Construction follows the " H " type of assembly, two concrete poles, 61 feet long, being set in

* *Elec. Review,* vol. 92, No. 2,379.

the ground about 50 feet apart, connected near the top by a horizontal crossarm of steel or concrete built in sections. In diameter the individual poles taper from 19.7 inches to 9 inches, and the weight is 8,000 lb. The relation of transverse strength to weight is a good deal lower than an economically designed steel structure, but the cost of the concrete support is proportionally low. Freight and handling form perhaps the principal objections.

In the Swedish installation it will be seen the concrete supports play the part of flexible frames. Heavier construction of steel is required at dead ends. However, there is ample scope for guying the concrete poles fore and aft and attaining any desired measure of longitudinal stability. According to R. D. Coombs, who has long been identified with mechanical developments in transmission-line engineering:

> "The most commonly used mixture is 4:2:1 broken stone or gravel, sand, and Portland cement. It should be mixed wet, using carefully selected materials, and tamped or chromed to eliminate air bubbles. Such a mixture, when well made, has an average compressive strength of about 1,000 lb. per square inch in seven days, 2,400 lb. per square inch in one month, 3,000 lb. per square inch in three months, and 3,500 lb. per square inch in six months. If conditions make it desirable to use high working stresses, a month or more should be allowed to elapse before new poles are subjected to severe tests."

This matter of ageing is here credited with the importance it merits, and the argument sometimes used that the concrete pole may be made up on the job is disposed of. Under the best conditions, a carefully fabricated pole is a little inferior to wood, it is heavier and costs appreciably more, it requires far more careful installation and a larger erection crew. It furthermore has no insulation value, which is sometimes an asset of timber. Notwithstanding these facts, the general tendency for good timber to become more and more scarce and the probable

cheapening of fabricated concrete will lead to a gradually increasing use of the latter.

According to Ludwig Kallir, concrete poles have met with very successful application in Austria, most of them being poured in a tapering I section, the web being pierced at intervals to reduce the weight. Nevertheless, the great weight of the structures renders it necessary to manufacture them on the ground, and even so the manipulation and setting of the supports is difficult in addition to which the problem of ageing becomes embarrassing. The following figures are given by Kallir relating to the poles most recently employed:

TABLE 33.—*Data on Concrete Poles used in Austria (Kallir).*

Type of pole	Suspension	Strain
Section	I	□
Number of circuits	1	1
Voltage	60 kv.	60 kv.
Height, above ground (ft.)	54	54
Test load (lb.)	1,320	4,400–6,600
Total weight	20,500	28,000–35,000

With steel tower construction it will be found that the maximum horizontal test load is of the order of two and a half to three times the weight of the structure. In the case of the concrete pole of the foregoing design, this is seen to be reduced to about one sixth the weight, and except for the local scarcity of steel and timber, concrete construction would not be competitive.

Rigid Towers.—If a general survey be made of engineering practice on transmission lines of 60 kilovolts or more, it will be found that probably at least 98 per cent. of the total mileage is built with steel towers. It will, therefore, be appreciated why this section of the treatise should elaborate steel tower practice somewhat fully. Long distances from the power source require high voltage, which in turn calls for long cross-arms and, in conjunction with heavy conductors, leads to severe torsion loads on the structures. A substantial structure, square in plan, with heavy corner posts and braced horizontally as well as in its vertical panels, has, therefore, been developed to a very

FIG. 43.—CONCRETE SUPPORTING STRUCTURE FOR THE 132-KILOVOLT LINE FROM TROLLHATTAN TO WASTERAS (SWEDISH STATE WATER-POWER BOARD).

[*Facing page 128.*

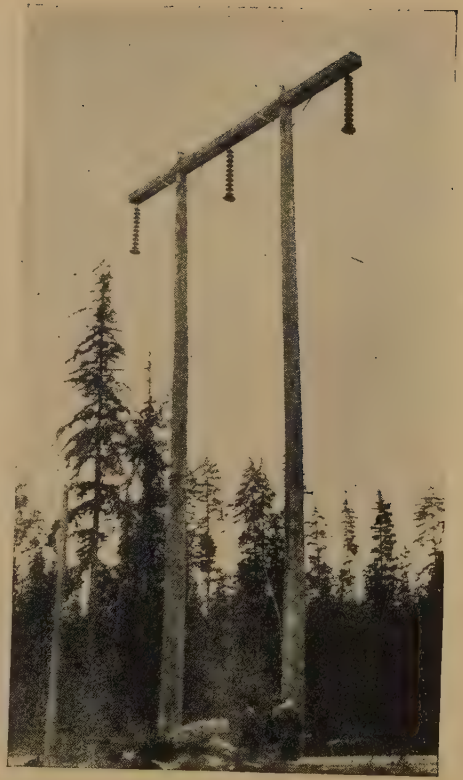

FIG. 44.—A 165-KILOVOLT LINE CARRIED ON TWIN CEDAR POLES SHOWING THE STANDARD CONSTRUCTION.

FIG. 45.—ANCHOR POLES ON A 165-KILOVOLT LINE.

[*Facing page 129.*

advanced stage, and represents the high-water mark of power-line construction. Whilst the twin wood pole is still used to a small extent for high-tension construction, it can obviously accommodate but one circuit on a given right-of-way, whereas the steel structure can support two or even more. Further, the span length is seriously limited, because few regular timber poles can be obtained longer than 60 feet, and with 8 feet submerged and a further 8 feet deducted for the length of insulator and distance to the vertex, only 44 feet remain for the sag combined with the ground clearance. Under the usual code of regulations this would lead to a maximum sag on the conductor of 19 feet, corresponding to a maximum span length of 300 to 400 feet. A steel tower line will normally be designed for two or three times this figure, involving a distinct economy of insulators, fittings, and hardware, as well as of labor. Moreover, with only one third the number of supports the mechanical and electrical reliability of the line will be greatly enhanced, and the cost of inspection and maintenance correspondingly reduced.

As already indicated, the structural steel pole with a small area of base has been used in preference to the tower in some localities, but its mechanical status as compared with the tower is seen by assuming a horizontal load at the crossarm and taking moments around the base or ground line. Clearly the load in the main posts will vary inversely as the distance between them; in other words, will be the least with the greatest spread of the base. This fact shows the tower to be inherently a more satisfactory design than the lattice pole, because with the former the base has a width of 20 to 25 feet, whilst the pole has a base of only 2 to 4 feet. In Germany, as already mentioned, the lattice pole has been very widely used, but it will be found that practically every pole has to be set in a concrete foundation, and guy wires have often to be applied after construction. The use of this type of construction in America is virtually confined to urban districts, where the right-of-way is narrow. Whilst the tower is designed as a truss with determinate stresses in every

member, the pole is figured simply as a beam, and the lattice members are indeterminate, being put in merely to shorten up the unsupported strut length of the main posts. This defines the fundamental difference between the two supports.

Early designs of transmission tower were derived from windmill practice, and the first towers employed were simply windmill structures with a short crossarm to support two 50-kilovolt insulators, the third being at the apex. The first tower line of appreciable significance was that of the Niagara, Lockport and Ontario Power Co., built in 1905 to transmit from the Ontario power station, on the Canadian side of Niagara Falls, across the gorge and through New York State to Syracuse, more than 200 miles. Early experiences on this tower line are of interest. Many of the structures were designed as tripods, others were built with tubular members, and in some cases the experiment was tried of filling the tubes with concrete to eliminate internal corrosion; the result, however, was a tendency for the tubes to split in winter. A few years after this line began operation at 60 kilovolts, the use of suspension insulators and 110 kilovolts operating pressure were introduced, and immediately tower design began to take on a new aspect. Two circuits were used instead of one on each tower, and crossarms were greatly increased in length, so that the torsion on the structure in the event of an unbalanced load was of great importance. During the ten years from 1910 to 1920 a number of designs were introduced, but the one achieving the greatest permanence was that supporting the two circuits in approximately vertical planes on either side, there being three crossarms for six wires. The individual weight of the structure varied from 4,000 to 12,000 lb., there being a tendency to increase during this period, owing to the fact that many of the earlier towers were too light. Anchor towers for special construction might weigh considerably more. The normal height of towers for economic design generally varied from 60 to 90 feet, though structures of more than 400 feet were built to carry the line across a wide waterway or ravine. Although, as in-

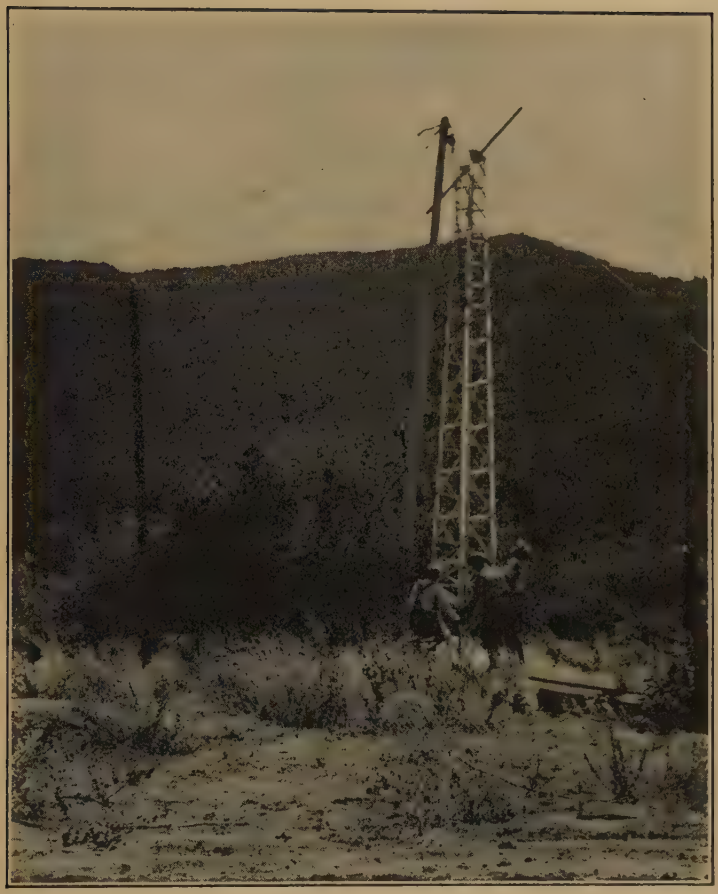

FIG. 47.—HOISTING A LATTICE STEEL POLE INTO PLACE BY USE OF A TIMBER GIN POLE.

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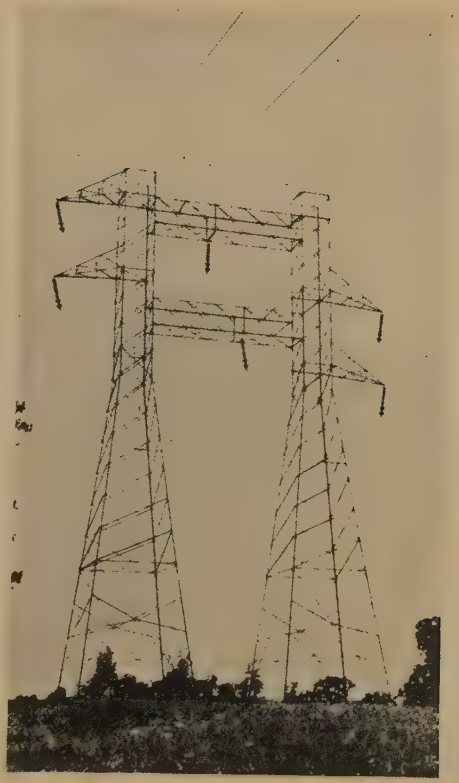

FIG. 48.—TRANSPOSITION TOWERS FOR A DOUBLE-CIRCUIT 220-KILOVOLT LINE.

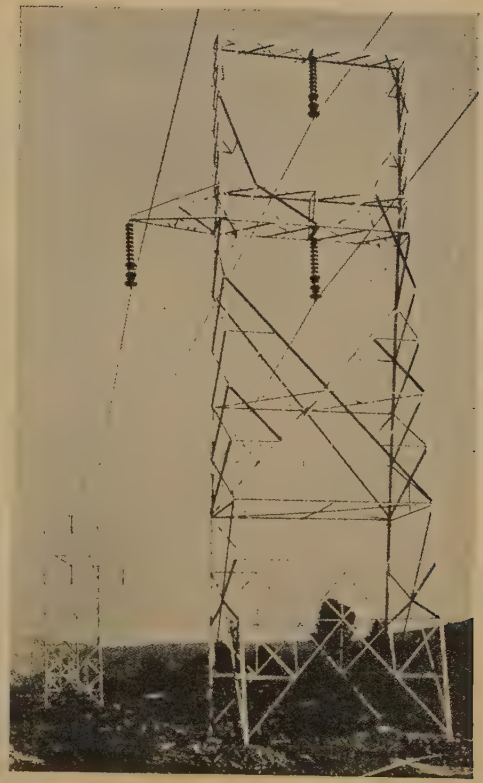

FIG. 49.—TRANSPOSITION ON A SINGLE-CIRCUIT 220-KILOVOLT LINE.

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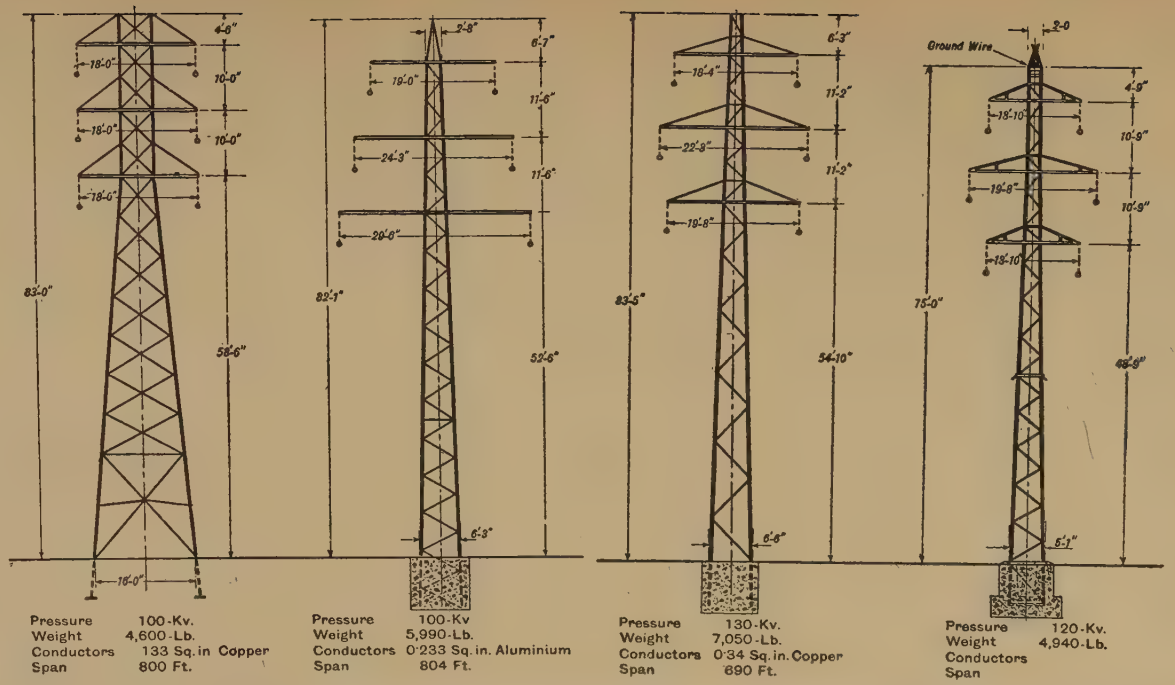


FIG. 46.—Double circuit structural steel supports for high-tension lines as used respectively in America (Pacific Gas and Electric Co.), Germany (Sachsichen Landes Elektrizitatsversorgung), Italy (Societa Trentina di Elettricita), and France (Soc. de Transport d'Energie de L'Est).

dicated above, the double-circuit tower was found to be both economical and mechanically satisfactory, the single-circuit structure also came into wide use. It is true that two such towers will require double the width of right-of-way that will accommodate a single two-circuit design, but in mountain and desert regions this has little weight. At the same time, a somewhat higher degree of stability is realized when the wires are not supported immediately above one another. For high altitudes in mountain terrain, where sleet and snow are frequently met, the experience known as "sleet jump," by which a wire may lose its coating of ice and whip up into contact with the conductor above, is entirely eliminated, because the points of suspension are in a horizontal instead of a vertical plane. It might be interpolated here that while in European practice attempt has been made to adhere to an equilateral triangle for the disposition of conductors, in America no such effort has been made. The spacing is laid out with a view to mechanical simplicity, and electrical balance is obtained by transposing the line wires from

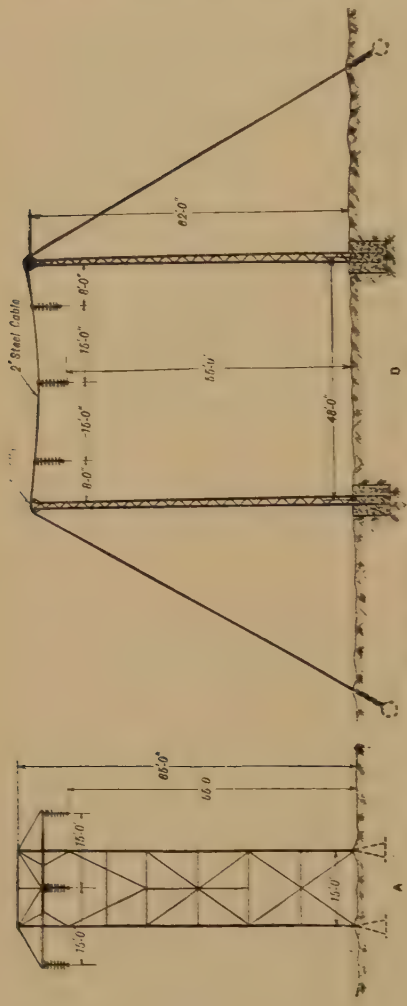


FIG. 50.—Conventional (A) and proposed flexible (B) design for high-tension line supports with high mechanical loading.

one position to another at certain fixed transposition points. In view of the extremely long spacing distance called for by voltages of 220 kilovolts and over, the single-circuit design is coming into wider use day by day; it yields adequate spacing without a very heavy structure, and affords easier maintenance and inspection. Somewhat greater reliability can be secured by routing the two single-circuit tower lines in different ways, but this plan involves two distinct surveys, and is not usually followed. The attitude towards single-circuit construction is to view it as being mechanically superior to double-circuit, but to justify its extra cost only in very mountainous country or for lines of unusually heavy capacity where the greater capitalization may be absorbed.

Flexible Frames.—Being erected upon a square base, with steel or concrete foundations and four heavy corner posts, the conventional tower is usually regarded as non-yielding in a practical sense. It must, therefore, be designed to carry the shock and the entire load in the event of a broken wire. Obviously, this load will be much less with a suspension insulator than with a pin type unit where the wire is firmly bound or clamped, but in any event the unbalanced load is very considerable, and the tower is heavy because of it. Several investigators (notably Dr. G. Semenza, of Milan) have shown that a very slight deflection of the pole or other structure will relieve the unbalanced load by throwing a small excess length of wire into one or other span. This has led to the adoption of flexible frames (erroneously termed flexible " towers "), which permit of this slight movement along the line, but are strongly braced in the normal direction. It is also pointed out that a broken wire load on any particular structure is a very remote possibility, and that, in general, a rigid tower is designed to withstand a load which it may never experience in the whole of its economic life. Some merit, therefore, attaches to the argument that the flexible construction will be more economical in some instances, as well as equally reliable. One installation is especially noteworthy as an example, that of the Niagara Falls Power Co. transmitting some 150,000 kva. at 22 kilovolts from Niagara

Falls to Buffalo. Two lines of double-circuit flexible frames are used, each structure being 54 feet high from the ground level, and having three crossarms for the six conductors in the conventional manner. Each structure carries, in addition, three high-tensile steel ground wires, so that the total number of wires strung on each frame is nine. This, it will be observed, greatly increases the factor of safety, because the failure of one wire in nine is not so serious an unbalanced load as the failure of one in three. The frames consist of two heavy steel channel posts braced together with round steel tie rods and heavy angle-com-

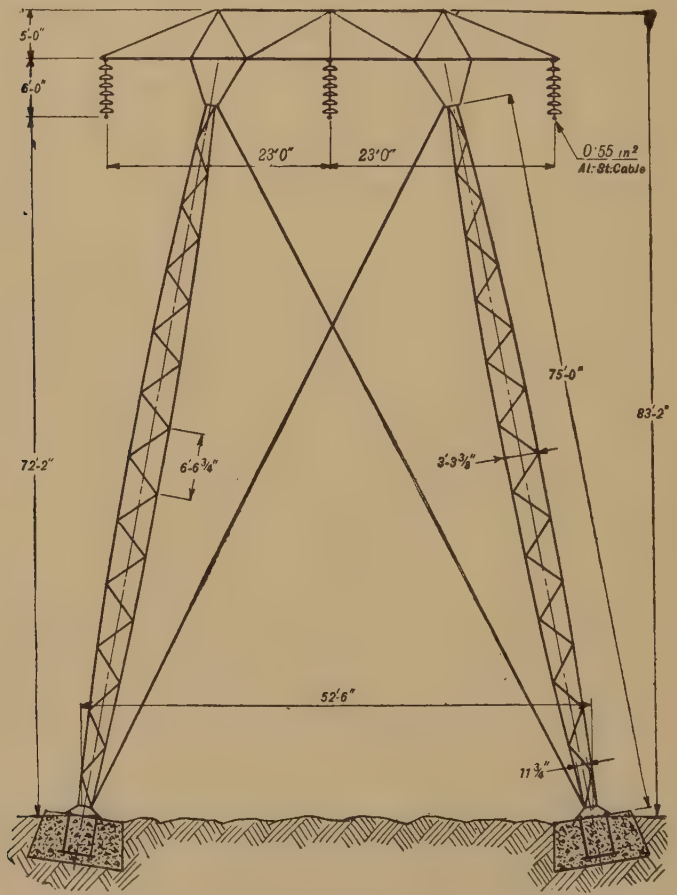
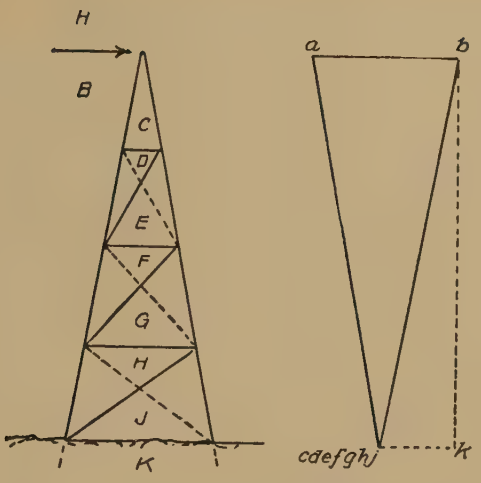
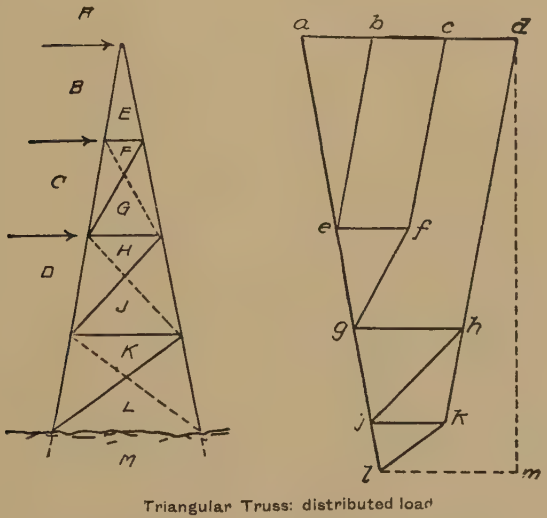


FIG. 51.—Continental design of flexible articulated steel transmission line support (G. Darrieus and H. Desbarres).



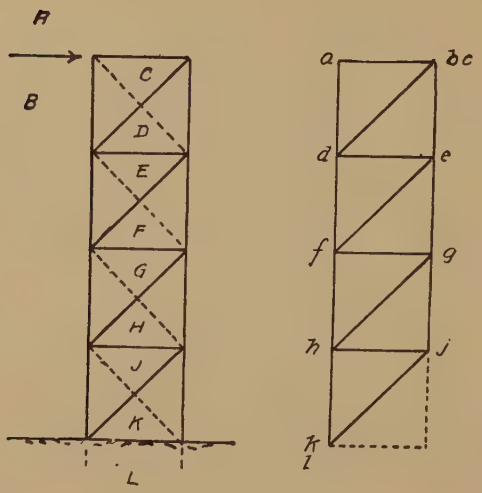
Triangular Truss: single load

FIG. 52A.—Elementary structure and force diagrams.



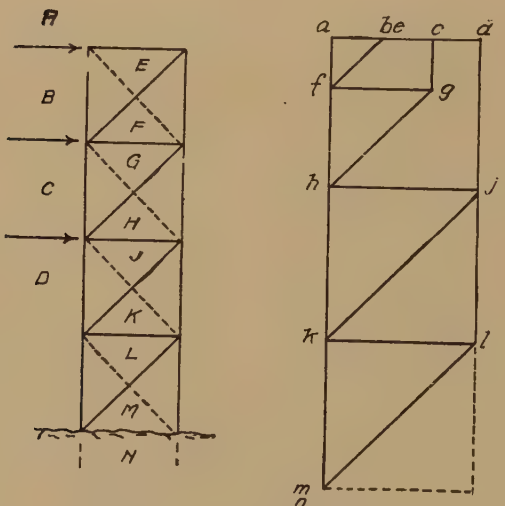
Triangular Truss: distributed load

FIG. 52B.—Elementary structure and force diagrams.



Rectangular Truss: single load

FIG. 52C.—Elementary structure and force diagrams.



Rectangular Truss: distributed load

FIG. 52D.—Elementary structure and force diagrams.

FIG. 53.—STEEL SUPPORTING STRUCTURE FOR THE 132-KILOVOLT LINE FROM TROLLHATTAN TO WASTERAS (SWEDISH STATE WATER-POWER BOARD).

[*Facing page 136.*

FIG. 54.—MALONE TYPE OF CONCRETE TOWER ANCHOR EXCAVATED AFTER TESTING, SHOWING THE SOLID CONCRETE BULB AND STEM.

FIG. 55.—CAVITY FOR MALONE TYPE ANCHOR AS BLASTED FOR RECEPTION OF CONCRETE.

[*Facing page 137.*

pression members. This bracing is adequate to care for all transverse loads arising from wind pressure on the sleet-coated wires with a sufficient factor of safety. Longitudinal loads, as already indicated, are compensated for by actual deflection of the frame, but to avoid a seriously cumulative deflection a rigid anchor tower is inserted at intervals. The spacing of these anchors will depend upon changes in direction or grade of the line, but will generally allow for not more than ten flexible frames in a row. It is sometimes found desirable to guy certain of the intermediate structures both front and back, so as to limit deflection and take up a portion of the longitudinal load.

A further development of the flexible frame has been to make it a little less flexible. Instead of the bracings being all in one plane with only two main posts, one structural manufacturer recommends the use of a four-post structure, the plan being a rectangle having its greater dimension across the line. This structure is appreciably more substantial than the last mentioned, and less recourse need be made to guys and anchors. The structure is, in short, a compromise between the rigid tower and the simple frame, both in weight and strength.

There is a distinct tendency with the heavy conductors now coming into use to relieve the structures almost entirely from emergency broken wire loads. If this can be done by the use of flexible insulator hangers or other device, a considerable weight of steel may be saved, and it has been calculated in a specific case that a 3,000 lb. structure can be substituted for one weighing nearly 8,000 lb. The construction indicated consists of two lattice steel poles some 50 to 60 feet high, erected 40 feet apart, with concrete foundations and solidly guyed. A high-tensile steel stranded wire is strung across the top of the poles, and from this the three insulators are suspended. Unbalanced loads are absorbed and damped by the method of suspension and guying, without being converted into heavy buckling loads on the steel structure. Crossarms and torsion loads are absent, windage on the structure is reduced, and stringing

is greatly simplified. It may also be practicable to convert the arrangement to a double circuit by the addition of not two, but one, extra column and a further span wire. No opportunity has yet offered to judge of the demerits of this construction, but it has a very powerful advantage in economy (Fig. 50).

Since structural steel is at least twice as strong in tension as in compression, great economy can be effected by eliminating all but the most essential strut members and substituting ties and guy wires. It is probable that future development of steel transmission supports of the flexible type will embody this feature to a wide degree. Most of these lines already carry two or more high-tensile steel wires strung tightly from pole to pole. This affords a great degree of mechanical stability, and is in a measure responsible for the satisfactory service records of flexible frames, besides, of course, affording electrical protection. An interesting pronouncement on the comparison of flexible frames with rigid towers was recently made by W. Borgquist and T. Nordell, engineers for the State Hydro-Electric Commission of Sweden:

> "One way to take care of stresses due to unbalanced pull is to make the majority of the towers of the plane type, with only a very limited strength in the direction of the line, and to insert anchoring towers, about one to every kilometer, which have great strength also in the line direction. The weak suspension towers between the strain towers then must be stayed by steel wires securely fastened to their tops and anchored to the adjoining strain towers. These steel wires equalize the pull resulting from conductor failure by transmitting the force along the line to the nearest strain towers. However, on more important lines with great areas and long spans, where the load on the towers is large, it is rather difficult to give the weak suspension towers just the right amount of mechanical strength in the direction of the line. It is necessary that the structures be sufficiently rigid to prevent the compressed members in the frame from bending out sideways,

but, on the other hand, the towers must have a considerable flexibility, because if they are too stiff the staying steel wires will be less effective, and the towers themselves will take up a good deal of the pull, to the detriment of their frames. To avoid this difficulty it has even been proposed to provide the weak towers with one link at either leg, so that the tower as a whole may swing out in the line direction. When built in this way, the tower evidently has no stiffness at all in the direction of the line, and becomes entirely dependent on the stay wires." *

Elements of Design.—Primarily, as seen in figure 52 there are two forms of truss used in tower design, the rectangular and the triangular, and it may be said that both are usually combined in one structure. For instance, it will nearly always be found that a single-circuit tower of the conventional shape, having all the wires in the horizontal plane, has a rectangular truss transversely to the line, and a triangle longitudinally to it. Either type of truss may have two forms of bracing, partially or completely diagonal. In the former the compression loads are all carried by horizontal members, and the tension loads entirely by diagonals; in the latter the diagonals carry both compression and tension loads, with a marked economy in the resulting weight of the tower. The stress diagrams in the figure are of the most elementary type, and show a concentrated load applied to one point near the top of the frame, and also a load distributed over the surface of the structure; the former illustrates a broken wire, and the latter a wind load. Obviously, with an isolated load applied near the apex of the triangle, no stresses will appear in the bracings, and this is of importance as related to the manner in which certain towers were formerly calculated and tested. The test load was applied at the center of the middle crossarm, and was calculated as the resultant of all the horizontal loads which would be experienced in practice. Actually, however, only the main posts were under test, and the trial afforded no criterion of the strength of the tower in the field.

* Proceedings International High Tension Conference, 1923.

The rectangular truss is usually provided with a strut at or near ground level to take care of the horizontal reaction. This is not necessary with the battered type, where the slope of the

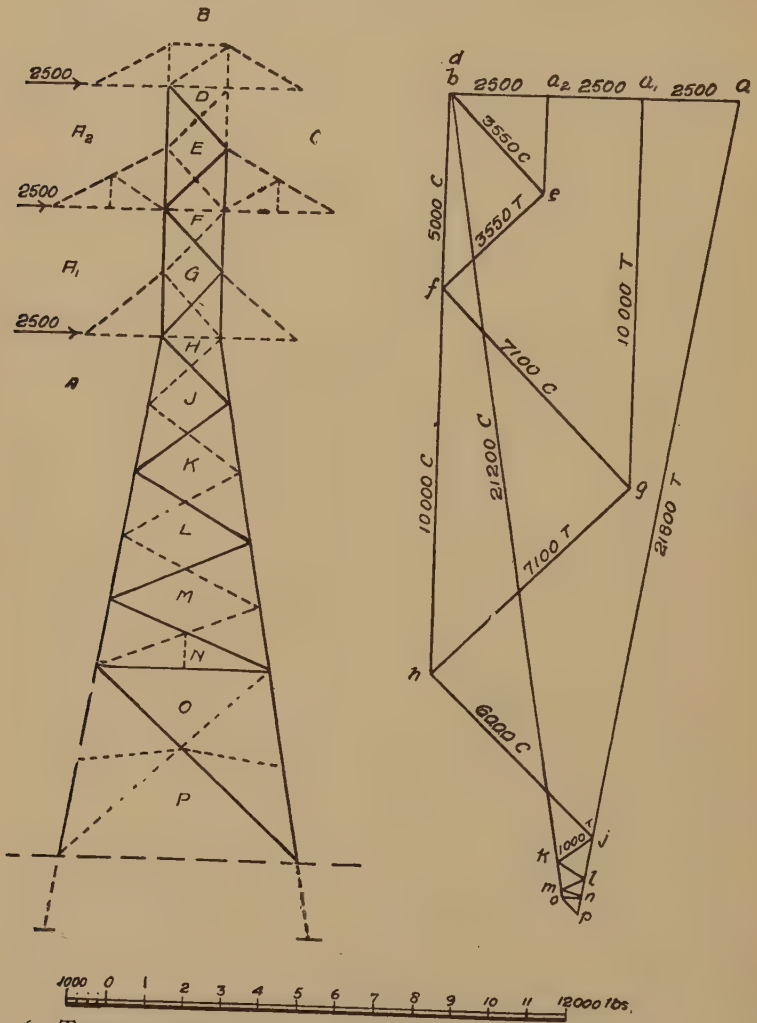


FIG. 56.—Tower structure and force diagrams for wind on wires (shear loads).

posts provides sufficient resistance to the horizontal thrust. Virtually the ground represents the horizontal member carrying a stress, and in good ground with secure anchors this ground

reaction is perfectly well taken up. Where the ground resistance is at all doubtful it is usually preferable to put in concrete foundations rather than to change the design of the tower.

In the actual fabrication of the towers mild steel angles and channels are used, varying in size from $1\frac{1}{2} \times 1\frac{1}{2} \times \frac{3}{16}$ inches for secondary members up to $6 \times 6 \times \frac{1}{2}$ inches or larger for the main posts of a strain tower. As practically all the members are in compression at some time, they are all angles, and no flat lacing is used.

Most designs are set out by a graphical method in which the horizontal loads are first drawn to a given scale, being derived from the sum of the wind loads on wires and tower, and, in the other direction, a broken-wire load at any given crossarm. These are usually supposed to act simultaneously, but must, of course, be calculated separately on two sheets and added in the respective members. In lettering the structure diagram it will be noted that redundant members, or those inserted to shorten up a strut length, are not essential parts of the system, and are ignored. Using the load line as a base, the force lines are drawn parallel to the respective members, working successively down the structure to the foundations. Bracings are designed to carry the shear and torsion loads into the posts as soon as possible, and towards the base of the structure the cross members become quite lightly loaded, and are, therefore, of lighter section. In drawing the shear load diagram some designers assume a neutral axis along the vertical center line, and confine their load diagram to one side of this (after first dividing the main loads by 2). Others carry the loads from one to the other side of the structure down one of the two systems of diagonals, also first taking one half the main load. This main load shown on the force diagram is itself one half the total load, because the other parallel face of the tower is simultaneously carrying its proportion.

From experience the designer can sketch out a suitable frame to meet the conditions, and then, by setting out the force diagrams as indicated, the individual stresses and weights of mem-

bers can be calculated. In connection with the force diagrams several points must be observed. The transverse loads will affect two faces of the tower, those parallel to the plane of appli-

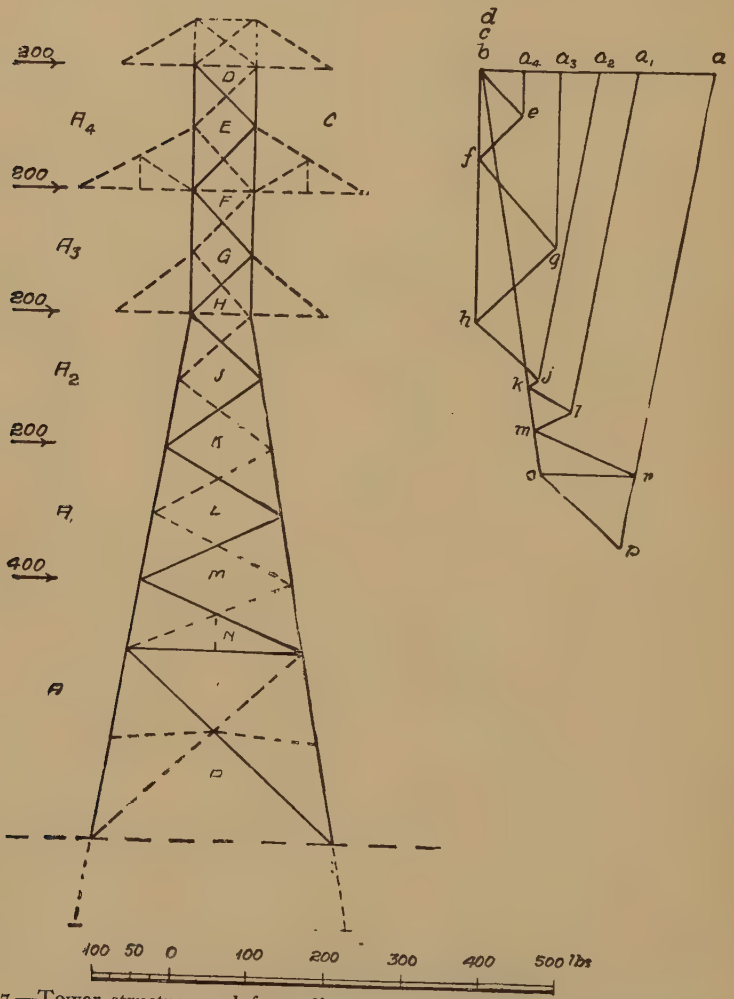


FIG. 57.—Tower structure and force diagrams for wind on tower (shear loads).

cation of the loads; conversely, the longitudinal loads will affect the other two faces at right-angles to these. The bracings will, therefore, be designed for whichever of these two is

the more severe. But the corner posts will take both these loads, and must be designed for their arithmetical sum. The torsion loads are at least as severe as the shear loads, especially

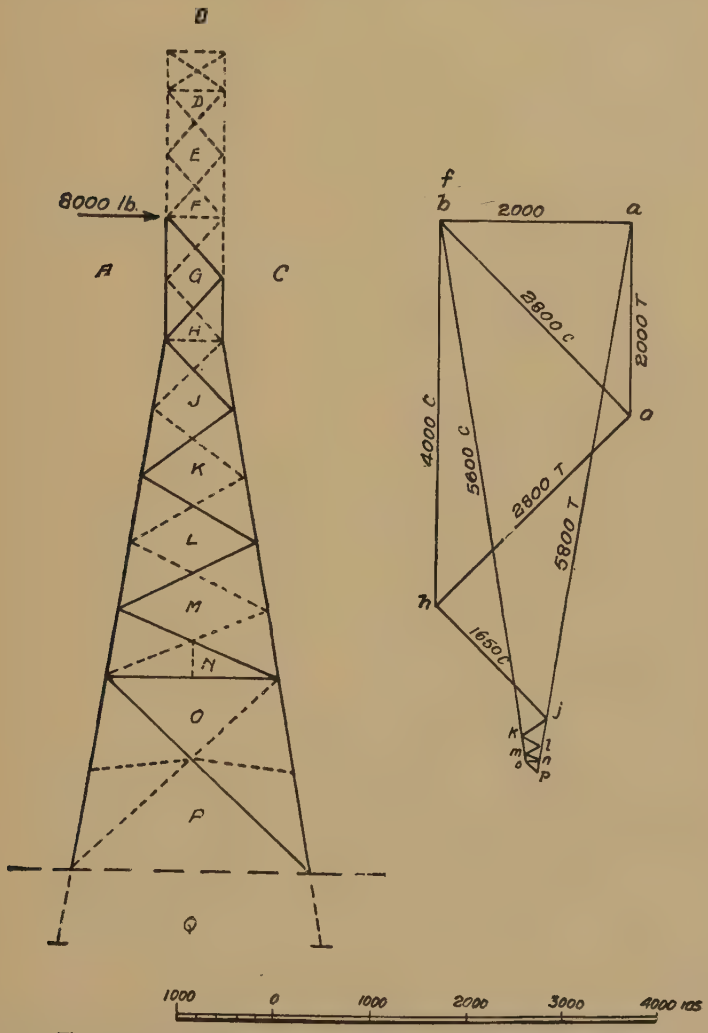


FIG. 58.—Tower structure and force diagrams for broken wire (shear loads).

on the bracing in the basket of the tower, and must be added to the greater of the two shear loadings before the section of

the bracings can be calculated. Weight loads are usually calculated only on the main posts, except for very heavy structures. In passing, it will be noted that most double-circuit towers are symmetrical except as regards the crossarms. Force diagrams are usually set out for (*a*) transverse wire loads, (*b*) longitudinal wire loads, (*c*) transverse wind load on the tower frame, and (*d*) torsion load due to a broken wire. As there are two parallel faces and two independent systems of bracing on each face, the load must be divided by 4 before laying out the base of the force diagram.

Practical Design.—The minimum essential data to be supplied by the electrical to the structural engineer are:

(*a*) Spacing and height of conductors.
(*b*) Number of conductors assumed broken.
(*c*) Assumed wind and ice loads.
(*d*) Safety factor on the structure.

Sometimes the minimum web thickness and minimum ratio of strut length to radius of gyration (L/R) are also specified, but these are best left to the experience of the structural engineers. Certain redundant members may have a thickness of only ⅛ inch without hazard, so that it is not economical to call for a minimum of 3/16 inch throughout. The maximum L/R ratio is commonly accepted as follows:

Main compression members	120
Secondary compression members	160
Redundant compression members	200

In passing, it might be indicated that a low L/R ratio need not mean a heavy section, and careful study of the properties of angles will often show where both weight and cost can be saved without impairing stiffness.

Structural steel angles are commonly rolled with a tensile strength of 50,000 to 60,000 lb. per square inch, and a yield point of about one half the ultimate figure. One prominent manufacturer of transmission towers has developed a structural steel having a yield point of 45,000 lb. per square inch, with an

ultimate elongation of more than 20 per cent. In fabrication, the steel for a given job is rolled, sheared, and punched in templates, lastly being hot-galvanized with pure spelter. The economic life of the structure will depend almost entirely upon the quality of the galvanizing, and this operation is, therefore, conducted with extreme care.

TABLE 34.—*Properties of Angles for Tower Members.*

Size.	Thickness. Inches.	Area. Square inches.	Lb. per foot.	Least radius R.	Maximum strut length. Inches.		
					L/R 120.	L/R 160.	L/R 200.
6 × 6	1	11.00	37.4	1.16	139	185	232
	¾	8.44	28.7	1.17	140	187	234
	½	5.80	19.6	1.18	142	189	236
5 × 5	1	9.00	30.6	0.96	115	153	192
	¾	6.94	23.6	0.97	116	155	194
	½	4.75	16.2	0.98	118	157	196
4 × 4	¾	5.44	18.5	0.77	92	123	154
	½	3.75	12.8	0.78	94	124	156
	⅜	2.86	9.8	0.79	95	126	158
3½ × 3½	½	3.25	11.1	0.68	82	109	136
	⅜	2.48	8.5	0.69	83	111	138
	¼	1.69	5.8	0.69	83	111	138
3 × 3	⅜	2.11	7.2	0.58	69	93	116
	5/16	1.78	6.1	0.58	69	93	116
	¼	1.44	4.9	0.59	69	94	118
2½ × 2½	5/16	1.47	5.0	0.49	59	78	98
	¼	1.19	4.1	0.49	59	78	98
	3/16	0.90	3.1	0.49	59	78	98
2 × 2	5/16	1.15	3.92	0.39	47	62	78
	¼	0.94	3.2	0.39	47	62	78
	3/16	0.71	2.4	0.40	48	64	80
1¾ × 1¾	5/16	1.00	3.4	0.34	41	54	68
	¼	0.81	2.8	0.34	41	54	68
	3/16	0.62	2.1	0.35	42	56	70
1½ × 1½	5/16	0.84	2.9	0.29	35	46	58
	¼	0.69	2.3	0.29	35	46	58
	3/16	0.53	1.8	0.29	35	46	58

The factor of safety on a steel structure may be understood in two ways: (*a*) the ratio of working stress to ultimate strength

in the individual members; and (*b*) the ratio of test load to ultimate crippling load on the complete tower. Generally (*b*) is too indefinite to use for designing, and the safety factor is assumed to apply to the load members. It may be asked why

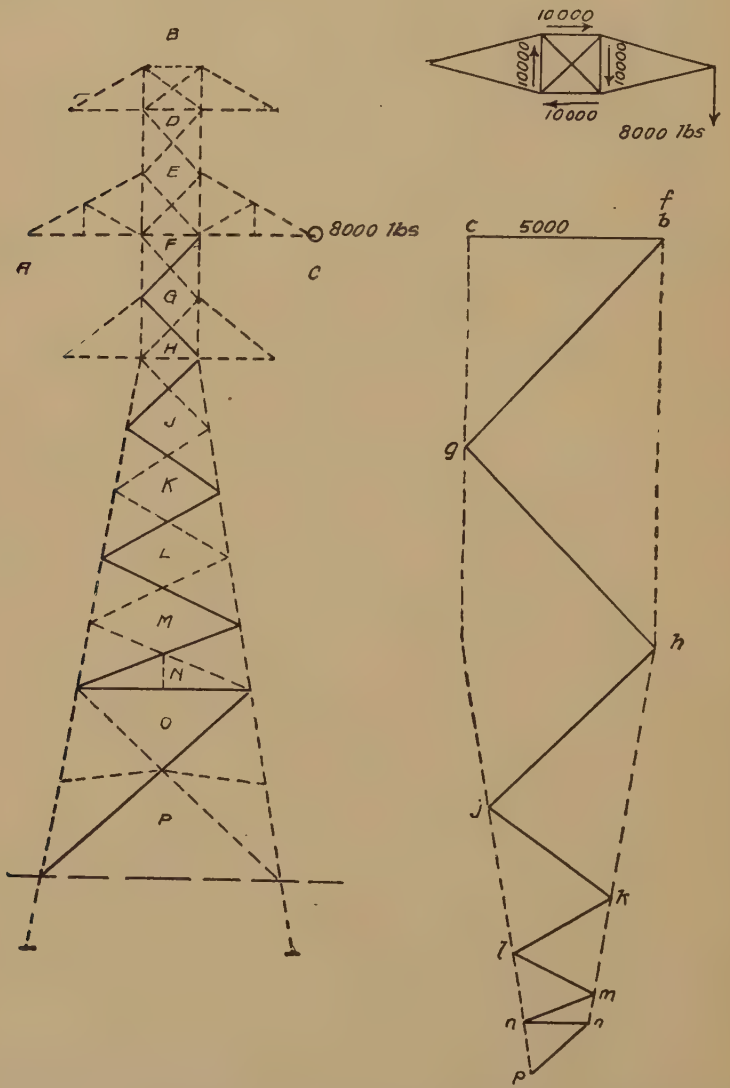


FIG. 59.—Tower structure and force diagrams for broken wire (torsion loads).

a tower which is designed for a factor of two or three on its members should fail under test with a load only 10 or 20 per cent. above normal. The answer is that with heavy loading the structure will become more or less deformed, leading to an entire redistribution of the stresses until one or other member fails. Where a specification calls for a given safety factor, it is usually assumed to relate to the unit stress in the members, and the safety of the tower as a whole is indicated by the severity of the test loads for which it is designed.

In computing the stresses a safety factor of two is common in the United States, and two and a half is specified in the rules of the Electricity Commissioners in Great Britain. For a safety factor of two and a half (based on the ultimate stress), the following unit stresses would be adopted:

	Lb. per sq. in.
Tension	20,000
Compression	20,000–85 L/R
Shear (bolts)	12,500
Bearing (bolts)	25,000

Some designers adopt the Gordon form of column formula—

$$\text{Compression} = \frac{20{,}000}{1 + \frac{L^2}{16{,}000\ R^2}}$$

but the straight line law quoted above is equally accurate within the desired range.

In the design of a line of towers a number of types must be worked out for the varying conditions on a given system. Generally these various designs will be limited as much as possible, although the writer is acquainted with a line only eighty miles in length which employs fourteen different tower designs. Obviously, this is not economical, and it is far better to use extension lengths or other device to make a given design fit different conditions. Two or three designs must, however, be adopted, one the standard suspension tower, which is designed for a maximum longitudinal load of one or two broken wires, to-

gether with a side load due to wind on all the wires and on the structure, as well as in some specifications the side pull of an angle of 5 to 10 degrees in alignment. Next an anchor tower is designed with heavier members, to allow for three or more

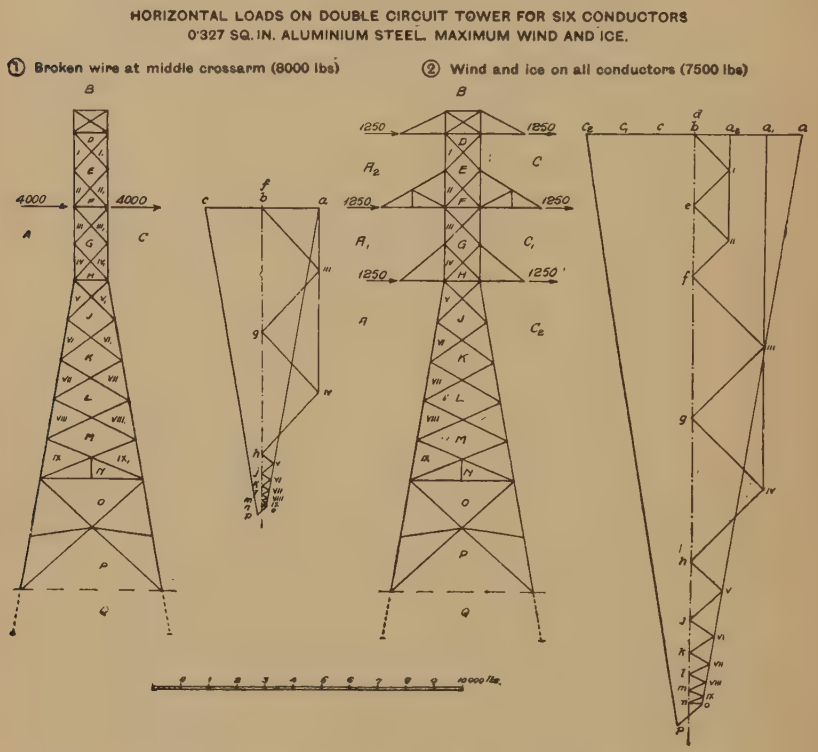


FIG. 60.—Tower structure and force diagrams (alternative method).

conductors to be simultaneously broken with full wind and ice load, as well as the side tension of an angle of 45 degrees. The dead-end tower used at terminal points, long crossings, and elsewhere will be designed still heavier, as it will permanently carry the combined loads in all the wires, and in general it will be designed with lower unit stresses than the other towers. For good electrical and economic reasons, dead-end points are reduced to the very minimum, and even anchor structures are kept as few as possible by eliminating abrupt changes in align-

ment. In a modern two-circuit high-tension line more than 100 miles long somewhat over 600 towers were recently installed, in the following proportion:

	Per cent.
Suspension	87
Anchor	12
Dead end	1

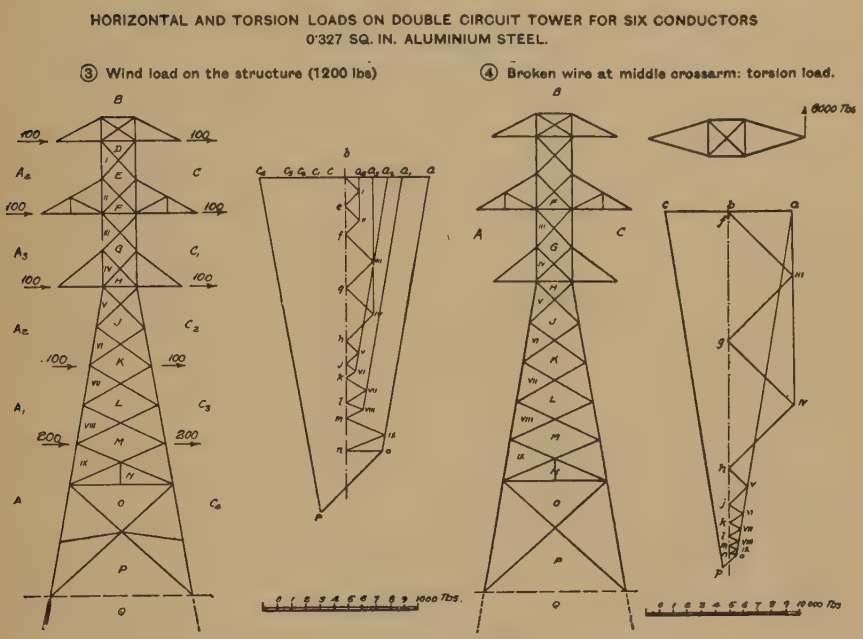


FIG. 61.—Tower structure and force diagrams (alternative method).

A somewhat lighter construction is sometimes substituted for the anchor, and termed a "semi-anchor," and this is often combined with an "A" form of insulator assembly, the tension permanently applied to the crossarm being dependent upon the angle of the "A." Certain loads in excess of a suspension point are taken up by this system, due to the more restricted swing of the insulators, and the tower will, therefore, be designed for them.

Other special construction is called for in transposition towers

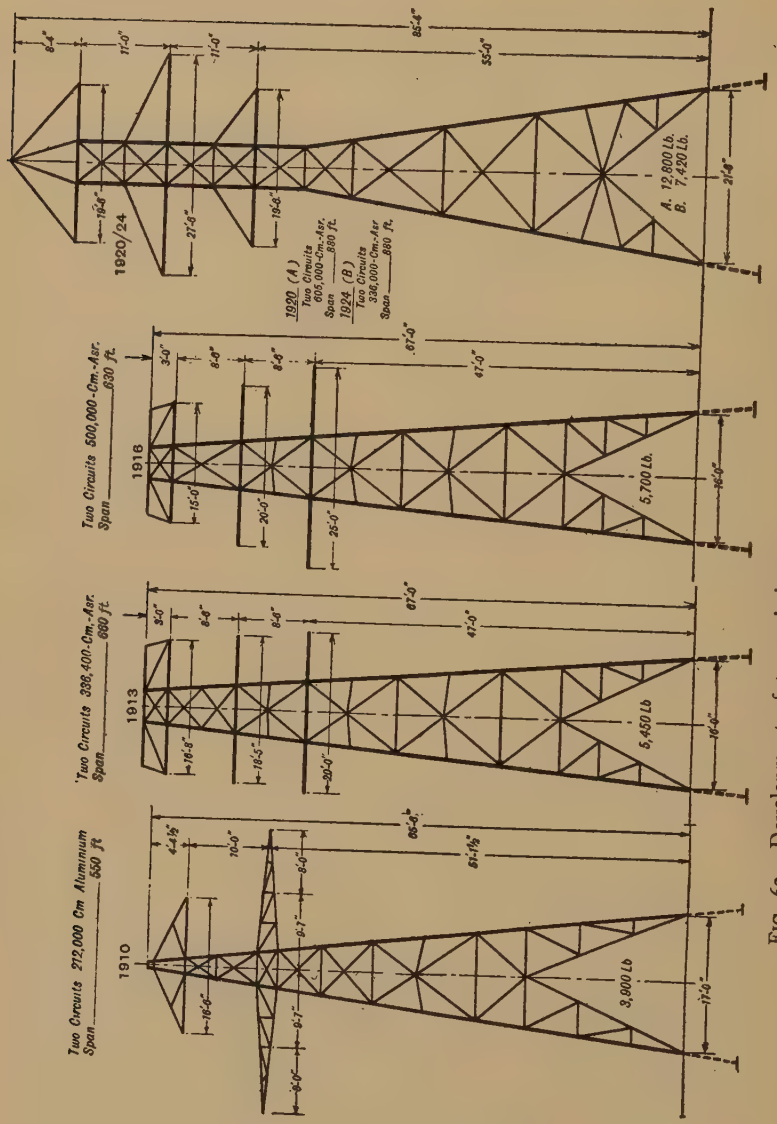


FIG. 62.—Development of transmission tower practice by the Hydro-electric Power Commission of Ontario during the years 1910 to 1924.

where the conductors are brought out to occupy new positions. Such towers must have an extra long crossarm, and the structure is braced to carry the additional torsional loads.

The customary length of span in high-tension line work is at present from 800 to 1,200 feet. Occasion requires a crossing of considerably more than this, and special construction must be adopted. In one crossing of the St. Lawrence River, near Three Rivers, Quebec, the length of span is 4,800 feet, and the height of the tower is 450 feet. Whilst it is possible to anchor the wires to such a tower, this is not usually done, and the conductors are usually carried over an insulated saddle and anchored to a short structure set 100 or 200 feet back. In this way the high tower need not be designed for the whole of the horizontal reaction necessary, which would call for a much greater weight of steel.

Whilst it is almost universal practice to employ galvanized steel sections for tower structures, some discussion has gone forward relative to the value of galvanizing as a protection. In one instance it has been calculated that it would be cheaper to use ungalvanized sections ⅛ inch thicker throughout, the rate of deterioration of the heavy sections being somewhat less than that of the galvanized. On the other hand, where climatic conditions are favorable, galvanized structures are in perfect condition after fourteen years' exposure. Coal smoke, with its attendant sulphurous vapors, is distinctly detrimental, however, and in certain industrial locations it has been found necessary to paint the structures with red lead and oil paint, in which case repainting must be done after five years. Similarly, alkaline deposits in the soil have attacked the galvanizing of footing members. It seems to be assured that in open country free from such influences galvanizing will have a life of more than fourteen years, if it is good when installed.

The very general use of riveted structures on the Continent has led to the adoption of painting instead of galvanizing in European practice. Experience has, however, shown the very much shorter life of paint as compared with zinc, and the ex-

pedient has been adopted of spraying the members with a metallic coating by the Schoop process after erection. This method is expensive both in labor and material, and there is reason to believe that galvanized sections will come into greater use.

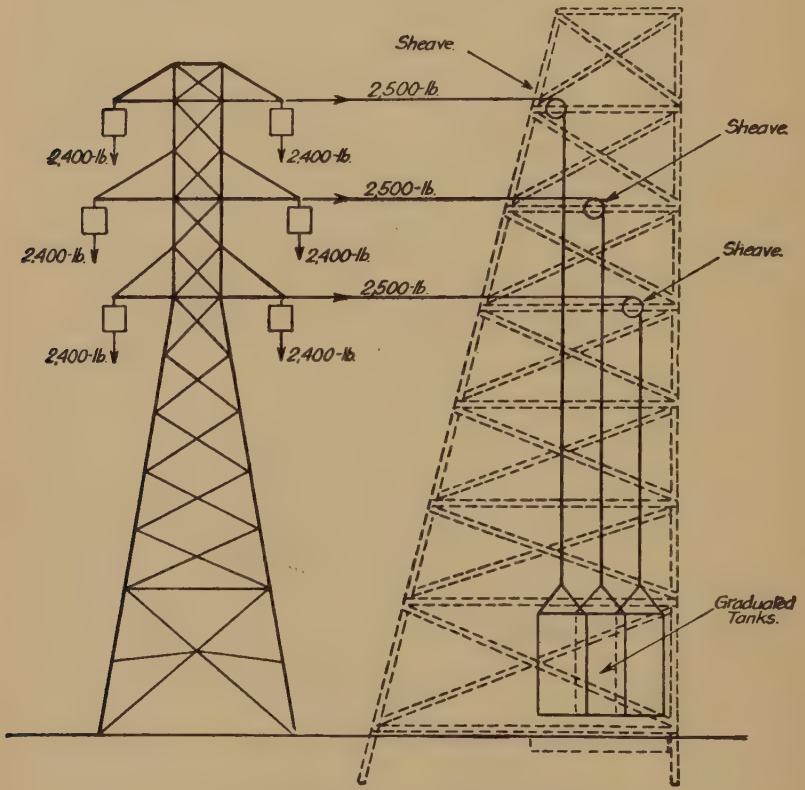


FIG. 63.—Diagram of tower-testing frame.

Test Loads.—From the viewpoint of the structural engineer, a tower is designed to stand up to certain definite test loads which are assumed to represent the maximum loads occurring in practice. They are calculated with such conservatism that provided the tower withstands them without failure it will be accepted.

The three main loads applied to the structure as a whole have already been outlined:

(1) The horizontal transverse load represents the effect of the wind pressure on all the wires of one span, allowing for the enhanced diameter due to ice, together with the wind load on the tower structure itself. At least one large power company designed its lines for a coating of ice all over the tower structure, the wind being calculated on the ice-covered members, but this practice is unduly conservative. In estimating the wind load one and a half times the area of the members of one face is assumed to be the exposed area of the tower. The unit pres-

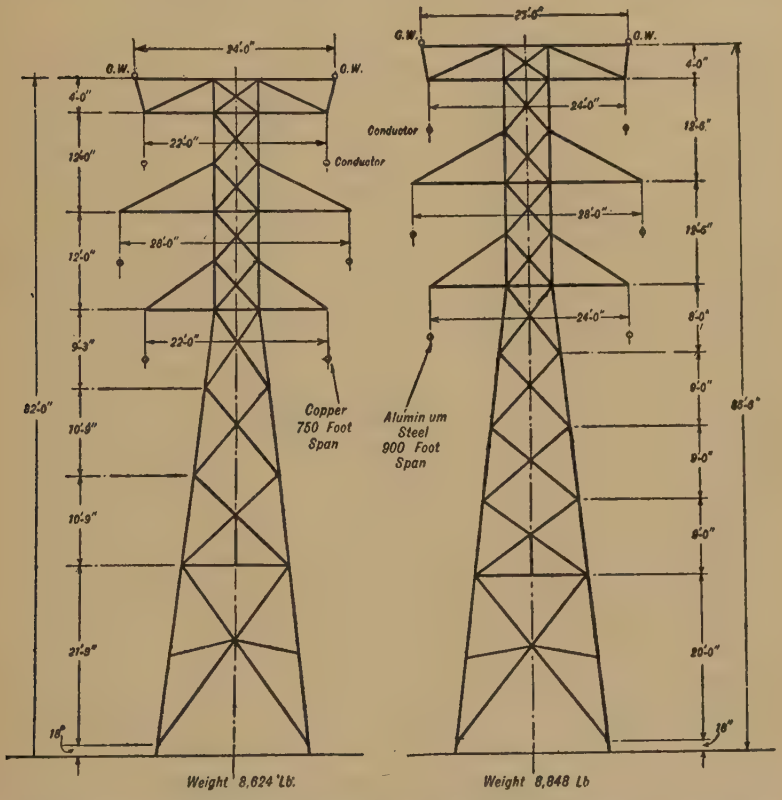


FIG. 64.—Towers designed for use on the same power system for copper and aluminum-steel conductors respectively (Nihon Electric Power Co., Japan).

sure in British practice is assumed to be 8 lb. per square foot of projected area, whereas in the United States this pressure is re-

lated to convex surfaces, and a load of 10 or 15 lb. per foot is assumed on flat normal areas. In any event, the wind on the structure is relatively of little significance as compared with the wind on the wires. It may be argued that it is impossible to estimate wind load on a structure before designing it, but a preliminary computation of the area of the tower can be made which will not be far off.

(2) Horizontal longitudinal load is represented by the tension of one or more wires applied to the ends of the respective crossarms. Some question exists, however, as to the value of this load, because if a wire breaks under conditions of the most extreme loading, it is not clear that its entire tension will come upon the crossarm. In the first place, the long insulator string will swing up into the unbroken span, adding its length to the wire, and so reducing the tension. In the second place, the conductor clamp will most usually slip at less than 4,000 lb., and in the third place, it is becoming customary to hook the insulator to the crossarms with a " safety eye " which has an ultimate limit of about 5,000 lb. The question may, therefore, reasonably be asked whether the longitudinal test load needs to exceed 5,000 lb. as a maximum, except for dead-end towers.

(3) Vertical load is represented, of course, by the weight of one span of conductor and insulators hung from each crossarm, in addition to the estimated weight of two linemen.

In an acceptance test all loads are applied simultaneously. A pair of tall stages of structural steel or timber are erected and reserved for this function. The tower is built up between them, and steel cables carried over sheaves at a suitable height in the stages are attached horizontally to the crossarms. The lower ends of the cables support steel water tanks graduated to give readings in thousands of pounds. Vertical loads are provided by weights attached to the crossarms. The tanks are gradually filled and the load brought up to the maximum. For minor tests, such as the breaking strength of a crossarm, chain tackle and a dynamometer may be employed, but the arrangement outlined above is considered best practice for a regular test.

Because of the great difference between ground foundations, it is impracticable to apply the test loads with the tower erected under practical conditions, and, instead of seating the structure

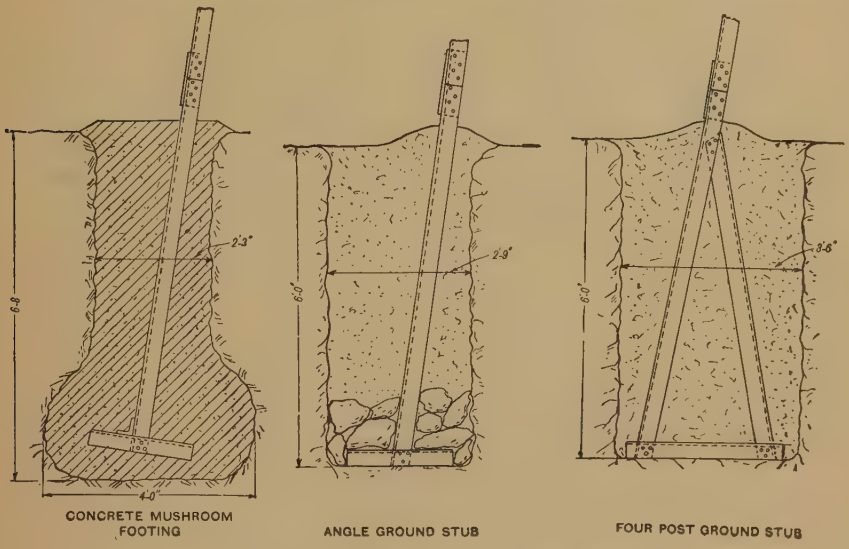


FIG. 65.—Three types of tower foundations.

on its regular footings, it is customary to bolt the main posts to a steel bedplate. Such a bedplate will, of course, take care of the horizontal reaction without any fear of distortion, and it is just possible that an unsatisfactory design of tower might pass its tests on the bedplate, whereas it would fail when erected on ground stubs. However, the elements of design and testing are now sufficiently understood to render this an improbable event.

It will be noted that all test loads are to be applied at the point of attachment of the wires. At an earlier period it was customary among some engineers to accept a "breast load" test in which the arithmetical sum of the loads was applied at the center of the middle crossarm. Obviously, this would give a false result, because not only would it eliminate all torsion stresses, but, if the line of the main posts intersected near the

point of application, no stress would appear in the bracings at all.

Foundations.—As every possible kind of soil is encountered in line construction, so it is to be expected that a wide variety of tower foundations will be used. Probably the majority in use are simple ground stubs, consisting of a heavy angle bolted to the foot of each of the main tower posts and extending 7 or 8 feet into the ground, each being bolted at its own foundation

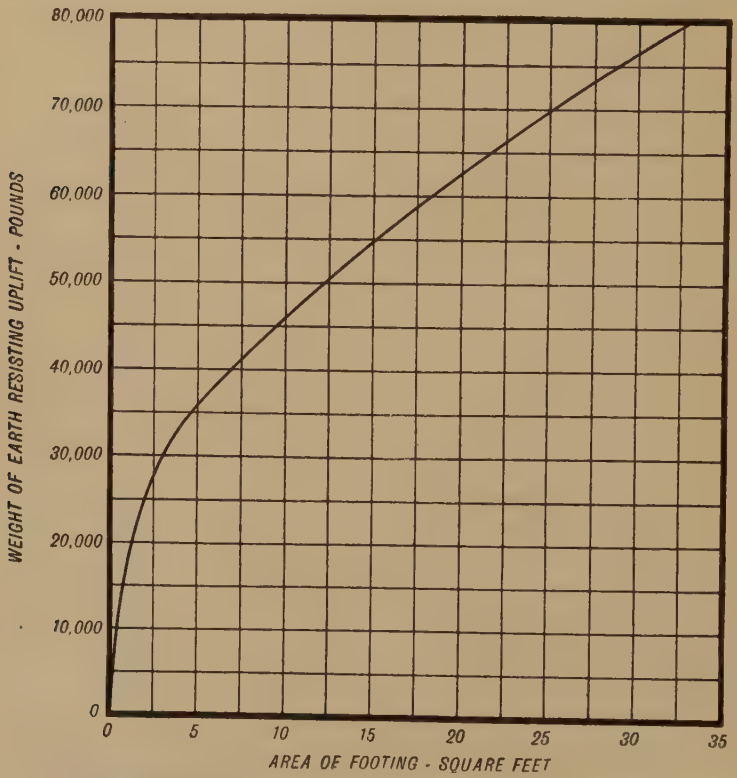
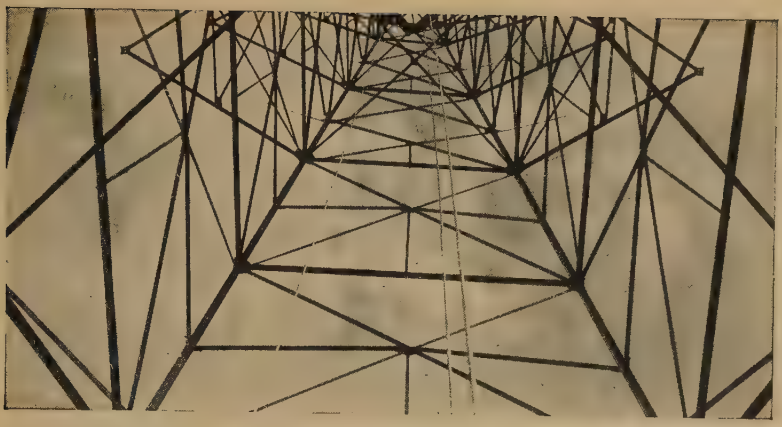


FIG. 66.—Calculated uplift on tower post with different areas of footing (designed maximum uplift should not be more than one half the above values).

to a horizontal steel grillage from 2 to 4 feet square. The principal load to be withstood by this foundation is the uplift of the tension post which may be in excess of 30,000 lb. Against this



FIGS. 67 AND 68.—EXPERIMENTAL LIGHT-WEIGHT TRANSMISSION TOWERS AT KYOTO UNIVERSITY, JAPAN.

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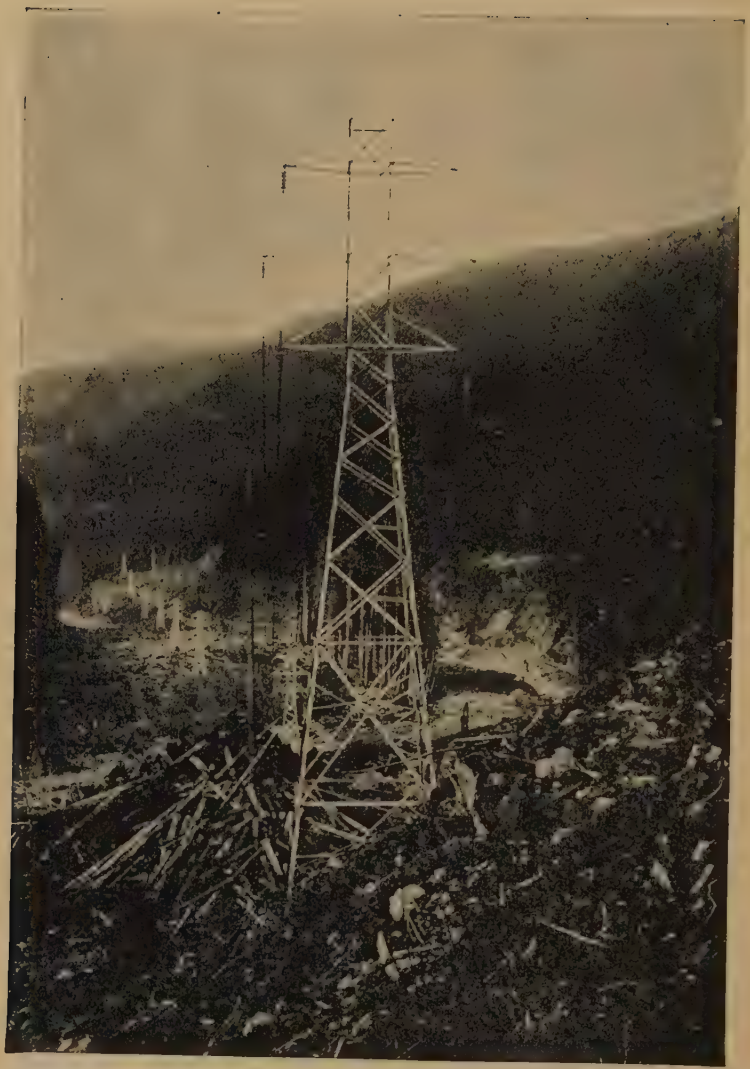

FIG. 69.—DOUBLE CIRCUIT 110-KILOVOLT LINE CONSTRUCTION IN MOUNTAINOUS AND HEAVILY WOODED COUNTRY.

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must be set the weight of the inverted frustrum of earth supported upon the grillage, and which is usually calculated as being 100 lb. per cubic foot, and having a slope inclined 30 degrees with the vertical. In calculating the necessary area and depth of the grillage it is usual to employ a safety factor of two. As a matter of fact, however, when the footings are properly set and the ground is reasonably good and dry, the strength is much higher than that calculated, as an appreciable shear strength is present in earth which has had time to become bedded down. The scissors tendency of the post members and the ground stubs to close up due to the horizontal reaction must also be resisted by the earth, and this has called for the use of more elaborate anchors than the above. Greater stiffness in the horizontal direction is provided by using a tripod or four-post anchor at each of the four tower foundations. This pyramidal frame is bolted at its base to the corners of the grillage, and at its vertex to the bottom of the tower post; its sole disadvantages are the somewhat greater difficulty of back-filling and tamping the excavation and the weight, which, in the case of the Big Creek system in California, amounts to nearly 25 per cent. of the entire tower steel.

Other means have been adopted to resist the horizontal forces, and on one transmission line a completely braced panel was used below ground level; this practice has not been repeated, but one tower manufacturer makes a specialty of connecting the bottom tension diagonal to the main post about 4 or 5 feet below the ground surface instead of immediately above it. This arrangement is standard on the system of the Alabama Power Co., and also upon several lines in Japan, where ground conditions are generally not very good. Not only is the device effective in neutralizing the tendency of the earth to yield and crack between the stubs, but it also forms a very cheap footing.

Concrete foundations are the most permanent, and are almost invariably used for strain positions where both the uplift and the horizontal forces are a maximum. There is also a tendency to employ concrete footings quite extensively for the

standard towers also where conditions permit. Generally, in desert and mountain regions the most difficult item in construction is that of transporting the necessary material, and when both water and cement have to be added the cost of construction increases very rapidly. In more favorable territory concrete can be readily mixed and placed, and its use at once reduces the amount of steel necessary for the foundations. On the other hand, the chief disadvantage is that the foundation gang must

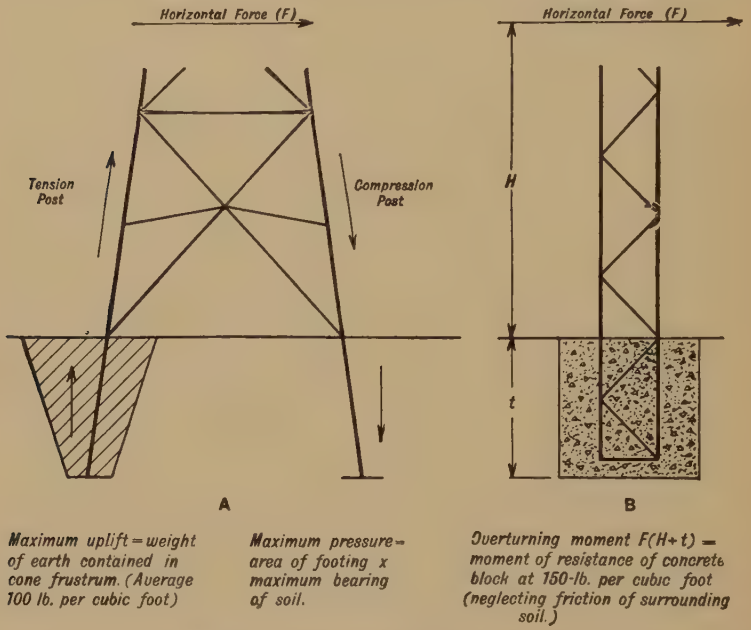

FIG. 70.—Estimating forces on the foundations of (A) steel towers, (B) steel poles.

work at least seven days in advance of the tower party in order that the anchors may be reasonably well set, and this spreads the work of construction over an undesirably wide territory; furthermore, a very large number of forms will be required. The mushroom type of concrete anchor is much more primitive than the above, and dispenses with forms entirely; it is made by digging a narrow hole about 6 feet deep and expanding the bottom, either by a spoon or by the use of dynamite. The stub

angle is then set and held in place by a template while the concrete is poured into the excavation. This form of anchor is not only effective in withstanding a much greater uplift than the simple ground stub, but it is almost as cheap and easy to set. Great satisfaction has been experienced with this type of footing on the system of the Pennsylvania Water and Power Co., a line of heavy construction using double-circuit steel towers. The maximum strength of the footing was never determined, but in field tests it failed to show any signs of distress with 70,000 lb. uplift.

A still newer development in concrete footings is known as the Malone anchor. It is a modification of the above, but has the very considerable merit that it involves the minimum disturbance of the soil. Briefly, four holes are drilled in the earth at the requisite angle for the tower posts, using a 5-inch post-hole auger and a wooden stage, with a guide to hold the auger post at the correct inclination. The depth of hole is from 5 to 8 feet, depending upon the height of tower and the amount of the reactions. A couple of sticks of dynamite are then loaded into the bottom of the hole, tamped, and exploded. As a result, a spherical chamber about 2 feet in diameter is expanded in the ground at the foot of the hole. This is cleaned out as far as possible, measured with expanding calipers, and the anchor post inserted in the hole and lined up by means of a template. The hole is then filled with a 3 : 1 concrete mix and thoroughly tamped. It is recommended that the towers should not be erected on the foundations until three weeks after the concrete has set. This forms the most simple type of foundation as yet developed; it involves the minimum disturbance of the ground, eliminates the uncertainty of back-filling, and yields all the advantages of a concrete foundation without forms. Labor and steel are both economized. In actual test, footings of this type have withstood more than 70,000 lb. uplift, and in a series of tests on six individual anchors the average uplift corresponding to a 1-inch yield at the ground surface was 60,800 lb., the average depth of anchor being 7 feet.

Modern Practice.—A series of tower designs is illustrated in the drawings, Figs. 72–74, and full particulars are given in Tables 36 and 37 and indicates the tendency of modern practice. Design " A " is of special interest, being the first double-circuit structure to be built for 220-kilovolt operation. The normal

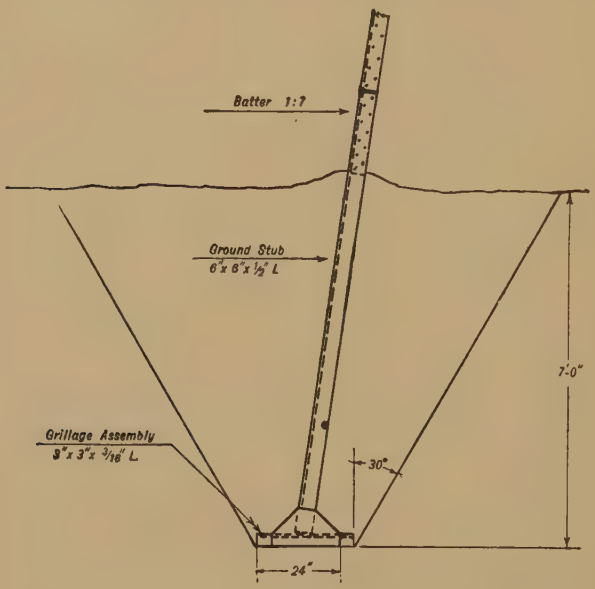

FIG. 71.—Customary design of "earth stub" footing.

span is 800 feet, with a maximum of 1,800, and the liberal vertical spacing of 15 feet will be noted, which, together with the necessary ground clearance, contributes to an overall height of 97 feet. Total weight of the tower is 8,000 lb., and of the corresponding dead-end structure 12,000 lb. Test loads for which the towers were designed were as follows:

TABLE 35.—*Test Loads on Towers for the Pacific Gas and Electric Co.*

Type.	Suspension.	Dead end.
Transverse load (at end of middle crossarm) (lb.).....	8,800	7,900
Longitudinal load (at extremities of crossarm).....	3 × 10,200	6 × 10,200
Vertical load (at extremities of crossarm).....	6 × 1,400	6 × 1,400

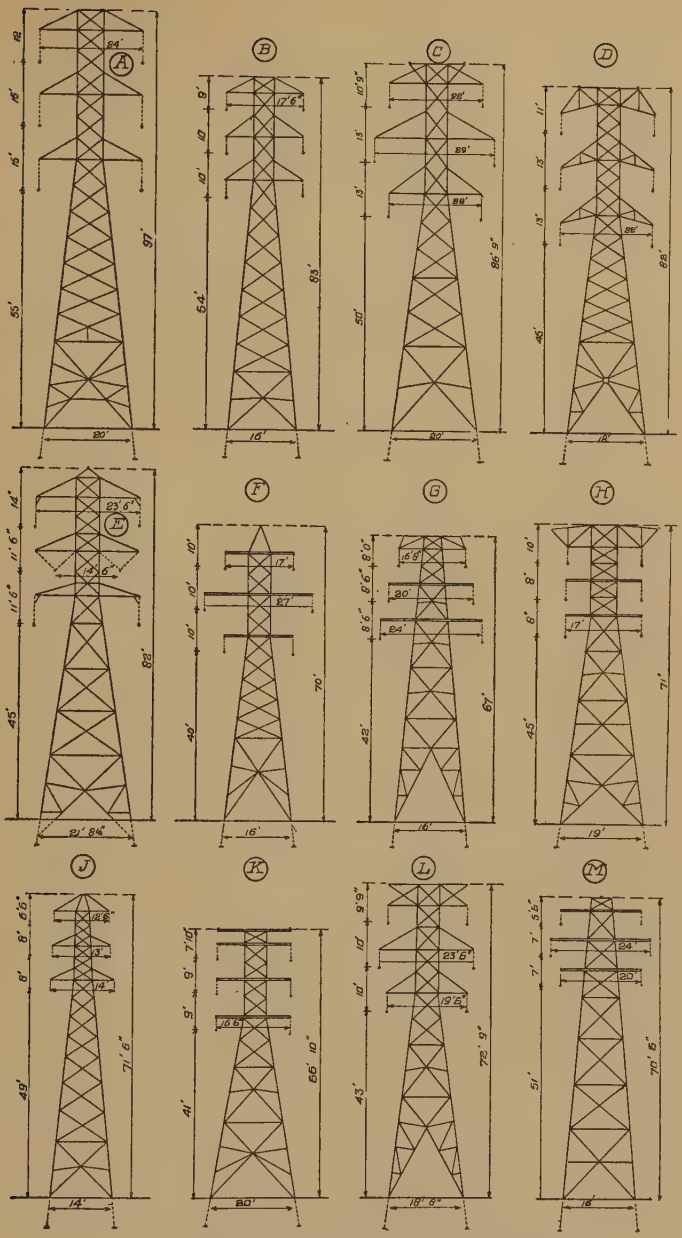

FIG. 72.—Double circuit tower designs (see Table 36).

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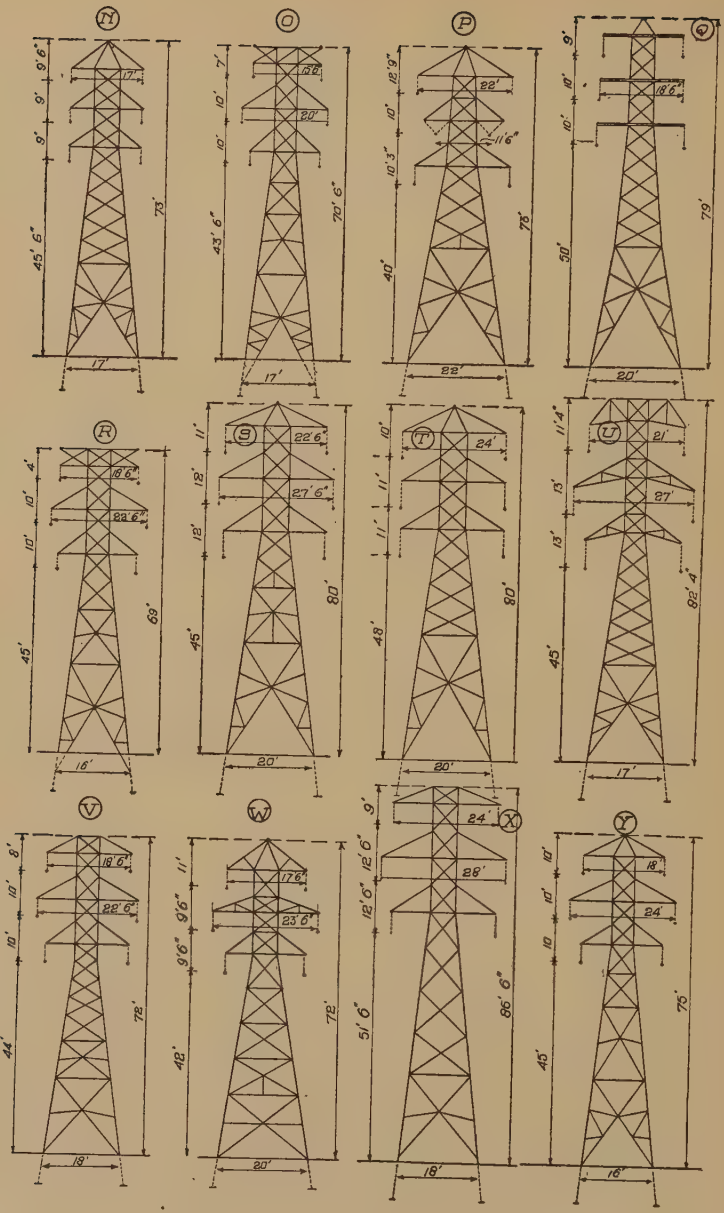

FIG. 73.—Double circuit tower designs (see Table 36).

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TABLE 36.—*Data of Double-Circuit Transmission Towers.*

	System.	Kilovolts.	Standard Span, Ft.	Conductors.	Size, Cir. Mils.	(2) Tension per Wire, Max. Lb.	Ground Wire.	Size, Cir. Mils.	(3) Tension per Wire, Max. Lb.	Weight Including Stubs.		Footings.		Tests on Standard Tower.			Manufacturer.
										Standard, Lb.	Anchor, Lb.	Standard.	Anchor.	Trans., Lb.	Longit., Lb.	Vertical, Lb.	
										8,038	12,334	Concrete	Concrete	8,800	20,250	14,400	Pacific Coast Steel Co.
										4,600	7,200	—	—	6,750	11,400	7,500	Pacific Coast Steel Co.
A.	Pacific Gas & Electric Co.	220	800	6 Copper	500,000	12,500	—	—	—	8,500	12,000	Ground-stub	Concrete	—	—	—	Blaw Knox Co.
B.	Pacific Gas & Electric Co.	110	800	6 Copper	168,000	4,000	—	—	—	5,166	9,989	Ground-stub	Concrete	—	—	—	Milliken Bros.
C.	West Penn Power Co.	130	560	6 Copper	212,000	5,000	2 Steel	110,000	3,180	12,900	14,200	Concrete	Concrete	—	—	—	American Bridge Co.
D.	Utah Power & Light Co.	130	650	6 Copper	212,000	5,000	2 Steel	110,000	3,180	3,700	4,700	Various	—	—	12,000	—	Milliken Bros.
E.	Knoxville Power Co.	150	800	6 Alum-steel	(1)500,000	12,000	1 Steel	192,000	5,600	5,400	—	Ground-stub	Ground-stub	—	—	—	Canadian Bridge Co.
F.	Southern Sierras Power Co.	88	660	6 Alum-steel	(1)212,000	4,200	—	—	—	4,800	6,200	Concrete	Concrete	—	15,000	—	Canadian Bridge Co.
G.	Hydro-Elec. Power Com. Ont.	110	600	6 Alum-steel	(1)336,000	6,300	2 Steel	76,000	2,200	4,511	7,881	Ground-stub	Ground-stub	1,500	3,650	—	Riter Conley Co.
H.	Shawinigan Water & Power Co.	110	520	6 Aluminium	250,000	2,500	2 Steel	110,000	3,180	5,554	6,880	Ground-stub	Concrete	10,000	8,000	9,000	American Bridge Co.
J.	So. California Edison Co.	66	700	6 Copper	212,000	5,000	—	—	—	6,780	12,766	Various	Concrete	14,000	3,000	13,000	American Bridge Co.
K.	Georgia Railway & Light Co.	110	620	6 Copper	212,000	5,000	2 Steel	147,000	4,200	—	—	—	—	4,000	9,000	4,000	American Windmill
L.	Inawashiro Power Co.	110	550	6 Copper	200,000	4,700	2 Steel	110,000	3,180	6,000	—	Ground-stub	Ground-stub	—	10,000	—	Milliken Bros.
M.	Washington Water Power Co.	60	750	6 Aluminium	168,000	1,650	1 Steel	110,000	3,180	3,111	—	Ground-stub	Ground-stub	5,000	7,000	1,200	American Bridge Co.
N.	Yadkin River Power Co.	100	700	6 Copper	105,000	2,500	1 Steel	110,000	3,180	4,800	—	Ground-stub	Ground-stub	—	—	—	Blaw Knox Co.
O.	Alabama Power Co.	110	600	6 Copper	133,000	3,100	2 Steel	110,000	3,180	7,700	10,500	Concrete	Concrete	—	—	—	Riter Conley Co.
P.	Cedar Rapids Mfg. & Power Co.	110	660	6 Alum-steel	(1)500,000	1,200	1 Steel	192,000	5,500	6,800	10,500	Concrete	Concrete	—	—	—	Watanabe Ironworks
Q.	Mississippi River Power Co.	110	700	6 Copper	300,000	7,000	2 Steel	192,000	5,500	5,620	9,800	Ground-stub	Concrete	—	—	—	American Bridge Co.
R.	Gumma Elec. Power Co., Japan	110	600	6 Copper	212,000	5,000	1 Steel	110,000	3,180	7,600	15,000	Ground-stub	Ground-stub	—	—	—	Milliken Bros.
S.	Ohio Public Service Co.	130	880	6 Alum-steel	(1)336,000	6,300	—	—	—	7,500	10,400	Ground-stub	Concrete	7,000	5,000	7,000	Blaw Knox Co.
T.	Victoria Elec. Comm., Australia	130	1,050	6 Alum-steel	(1)336,000	6,300	1 Steel	192,000	5,500	5,500	11,000	Malone	Concrete	15,000	—	11,500	Pacific Coast Steel Co.
U.	Kansas Gas & Electric Co.	130	850	6 Alum-steel	(1)267,000	4,700	—	—	—	4,875	8,415	Ground-stub	Ground-stub	10,020	12,000	10,800	American Bridge Co.
V.	Portland Electric Power Co.	110	800	6 Copper	250,000	5,700	—	—	—	7,500	10,000	Ground-stub	Ground-stub	—	—	—	Blaw Knox Co.
W.	Chile Electricity Co.	110	—	6 Alum-steel	(1)168,000	3,300	1 Steel	76,000	2,200	8,850	—	Ground-stub	Concrete	—	—	—	—
X.	Nippon Elec. Power Co., Japan	150	800	6 Alum-steel	(1)416,000	7,500	1 Steel	192,000	5,500	5,100	7,100	Ground-stub	—	—	—	—	
Y.	Blackstone Valley Gas & Elec.	115	600	6 Copper	133,000	3,200	1 Steel	110,000	3,180								

Note: (1) Aluminum section only. (2) Based on one half ultimate strength. (3) Based on one third ultimate strength.

TABLE 37.—*Data of Single-Circuit Transmission Towers.*

	System.	Kilovolts.	Standard Span, Ft.	Conductors.	Size, Cir. Mils.	(2) Tension per Wire, Max. Lb.	Ground Wire.	Size, Cir. Mils.	(3) Tension per Wire, Max. Lb.	Weight Including Stub. Standard, Lb.	Weight Including Stub. Anchor, Lb.	Footings. Standard.	Footings. Anchor.	Tests on Standard Tower. Trans., Lb.	Tests on Standard Tower. Longit., Lb.	Tests on Standard Tower. Vertical, Lb.	Manufacturer.
AA.	Southern Cal. Edison Co...	220	1,250	3 Alum-steel	(1)666,000	11,500	—	—	—	9,405	16,680	Ground-stub	Ground-stub	4,100	36,000	6,000	Pacific Coast Steel Co.
BB.	Southern Cal. Edison Co...	150	660	3 Alum-steel	(1)605,000	10,500	1 Steel	192,000	5,500	5,600	8,050	Ground-stub	Concrete	1,700	8,500	2,500	Milliken Bros.
CC.	Southern Cal. Edison Co...	60	750	3 Copper	212,000	5,000	—	—	—	3,544	4,952	Ground-stub	Ground-stub				
DD.	Great Western Power Co..	165	750	3 Alum-steel	(1)452,000	11,500	—	—	—	3,605	5,290	Ground-stub	Concrete	2,000	10,000	4,200	Pacific Coast Steel Co.
EE.	Great Western Power Co..	165	750	3 Alum-steel	(1)336,400	8,100	—	—	—	3,165	4,525	Ground-stub	Concrete	2,000	10,000	4,200	Pacific Coast Steel Co.
FF.	Pacific Gas & Electric Co..	220	750	3 Alum-steel	(1)518,000	11,000	—	—	—	5,100	7,270	Concrete	Concrete	5,250	19,500	10,650	Pacific Coast Steel Co.
GG.	Penna. Power & Light Co..	220	1,100	3 Alum-steel	(1)795,000	14,000	—	—	—	8,290	17,400	Malone	Malone	8,400	10,000	14,000	Lehigh Structural Steel Co.
HH.	Chile Exploration Co.....	110	660	3 Copper	168,000	4,000	2 Steel	110,000	3,180	3,300	5,400	Ground-stub	Concrete	4,600	6,700	3,000	American Bridge Co.
JJ.	Colorado Power Co.....	100	750	3 Copper	106,000	2,500	—	—	—	2,200	—	Various	Various	—	—	—	Riter Conley Co.

Note: (1) Aluminium section only. (2) Based on one half ultimate strength. (3) Based on one third ultimate strength.

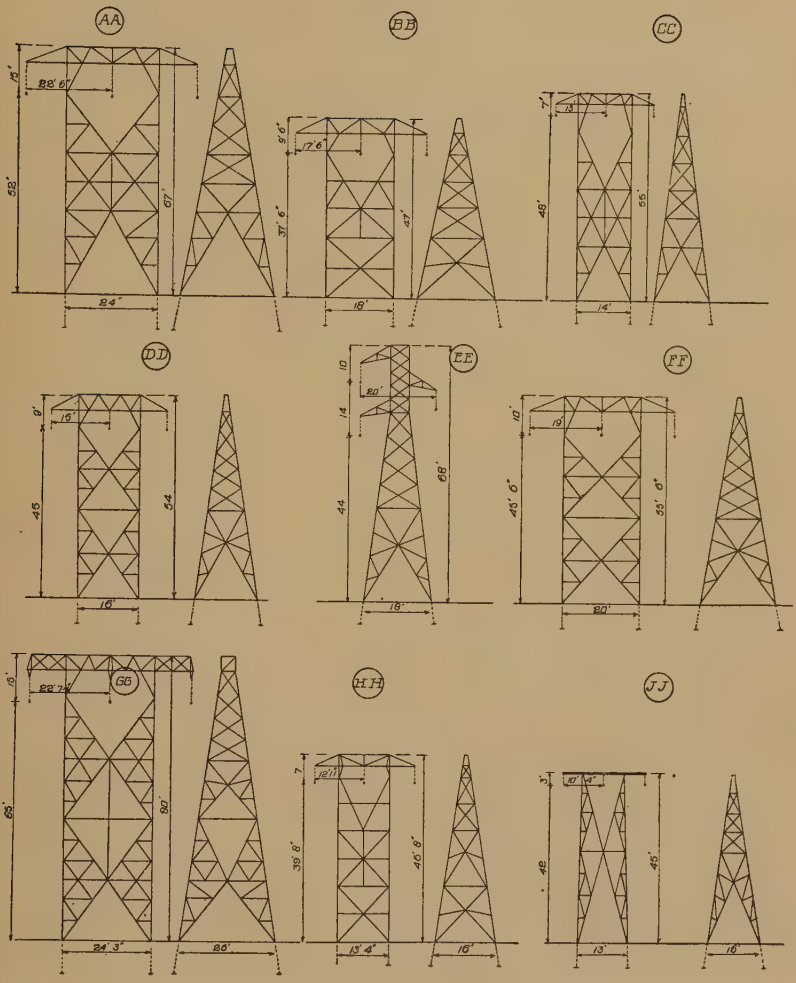

FIG. 74.—Single circuit tower designs (see Table 37).

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An unusual factor of safety is provided by the assumption that three conductors may fail on one side of the suspension tower.

Design " B " represents the structure used by the same company for its 110-kilovolt lines, and the design is similar, but has lower loading values. In " C " the offset crossarm will be noticed. This line is built in a sleet country, where ice may be expected to form on the wires, and the possibility of contact through excessive vertical displacement must be eliminated. Ground wires are intended to be strung at the ends of the topmost arms of the structure. The crossarm shown halfway up the tower forms no essential part of the structure, being intended for the customary telephone line. An interesting form of crossarm is illustrated at " D "; this was devised to maintain safe clearance, even with an insulator swing of 60 degrees from the vertical.

On the Knoxville Power Co.'s design " E " the middle conductor is tied in by the use of an additional insulator. This prevents swinging and " sleet jump " as effectively as an extended crossarm, and reduces the torsion loads on the tower. On the other hand, any tendency to increase the number of line insulators is sometimes considered unsatisfactory for reasons of operation, and the offset crossarm is more usual. These structures are designed for one of the heaviest power lines in America, carrying steel-cored aluminum conductors 0.39 square inch section on spans averaging more than 1,000 feet. The method of erection involves the lowermost tension member being joined to the main post below the ground level.

Designs " F " and " G " show the use of straight channel crossarms without any vertical tie rods. Such crossarms have ample strength in the horizontal plane but have sometimes been distorted during stringing operations in the field. The continuous batter of Tower " G " will be noted; this makes a secure foundation for the crossarms more difficult than with the usual parallel basket members. In view of the heavy conductors and long spans coming into use, it is generally being found more economical to use a tower with braced crossarms.

In the Shawinigan tower the most noticeable feature is the extended ground-wire support, which is devised to give the ground wires a greater coverage of the power circuits. Owing to the uncertainty with which the ground wire functions, it is doubtful if this arrangement has any substantial merit. Design " J ," of the Southern California Edison Co., is one of a 66-kilovolt line built in the year 1912. It shows an unusual ratio of height to base of 5.1, the average for most conventional double-circuit towers being 4 or less. The Georgia construction uses channel crossarms of equal length so that three conductors and one ground wire be in the same vertical plane. This tends to give minimum torsion loading and economical design where there are no sleet loads. Design " L " was fabricated by an American manufacturer for one of the most important power systems in Japan. The special top crossarm for two ground wires will be noted. There is an open question as to the relative value of one, two or no ground wires, and the tendency is to reduce the number or to eliminate this device entirely. A tower designed for two ground wires will be appreciably heavier than where none is contemplated. Tower " M," of the Washington Water Power Co., is an early type, and obviously not required to carry very heavy loading. Clearances are relatively short because the operating pressure is 60 kilovolts. The extended crossarm in this design was added after a thorough series of experiments to ascertain the effect of ice loading. The tests were made by the engineers of the Washington Water Power Co. under conditions simulating as closely as possible those of practice; weights were attached to the wire at intervals, and were suddenly thrown off, causing the conductor to whip upwards into contact with the one above. In this sense the present design is the progenitor of all extended crossarm towers, and a very distinct value must be assigned to the early experimental work by the engineers of the company.

In the Yadkin River structure the most interesting feature is the considerable width of basket which offers great resistance to torsion loads. At the same time, on a given base, a wide basket limits the slope or " batter " of the main posts, and so

increases the load upon them. The open base of this and most other designs is an essential feature where the line crosses cultivated country, because it permits the ground between the posts to be ploughed and sown. This is of the greatest importance when acquiring wayleaves from farmers and helps to reduce the annual cost.

Design " O " was one of the first to employ the foundation shown in which the junction between the lowest tension member and the main post is made below the ground. This device has been proved to take care of extremely high values of horizontal reactions without movement of the ground stubs, and is especially valuable in ground of uncertain character. In the next tower, that of the Cedars Rapids system, the basket is seen to be tapered or battered. This provides greater clearance for the upper conductors and greater resistance to torsion at the lower crossarm. These towers are of exceptionally heavy construction, forming part of a 110-kilovolt line which transmits 100,000 kilovolts over two circuits from Cedars Rapids on the St. Lawrence River through Canada, crossing the river near Ogdensburgh and terminating at Massena, New York. Design " Q " was one of the highest types of standard suspension tower built at the time when the Mississippi River Power Co. began construction. It carries six copper conductors of 300,000 cir. mils, on spans of 700 to 850 feet. The next double-circuit tower is one of a number fabricated in Japan on the basis of American designs. Whilst the steel can be rolled of high quality, the cost of fabrication is not so well advanced, as the mills are not yet thoroughly equipped with the necessary shearing and punching templates for tower production. For this reason, a number of gusset plates must be used at the various intersections, which practice puts up the cost of the tower. It will also be found that a very large number of bolts is required owing to the short length of the members. This is due to another reason, however. Most of the steel for a transmission line in Japan must be transported by bullock cart through the narrow winding streets of the towns, which

limits the length to about 12 or 15 feet. Owing to the prevalence of manual in place of mechanical handling, there is also a distinct weight limit. In normal conditions lengths of 20 to 25 feet between splices are common practice.

Designs "S" and "T" are interesting because they represent the practice of two different manufacturers in designing for virtually similar operating conditions. In "S" the diagonal tension members and horizontal struts will be noted; in "T" the double diagonal system is used. There is little difference in the weight of these two examples.

In the series of double-circuit towers surveyed it will be noted that reference has been made only to the suspension designs. The strain and anchor towers follow the same lines, however, except that they are built of heavier sections and are generally somewhat shorter.

In Design "AA" is shown one of the most modern designs of single-circuit tower for a 220-kilovolt line in mountain country. This form is coming into wide use, and represents a simple portal problem with knee and cross bracing. The side view shows the customary triangular or battered truss, with a double system of bracing. Such a tower has the advantage of being short, and therefore stiff for a given weight. On the Southern California Edison system the single-circuit tower of the design shown ("BB") is used throughout. The structure was designed for 150-kilovolt operation, and to increase the clearance for 220-kilovolt service, a braced four-post extension has been inserted, under the lowermost panel of the tower, the latter being jacked up 15 feet for the purpose. This operation was performed on the towers without a mechanical failure of any kind. The Great Western Power Co., it will be seen, uses a totally different form of single-circuit tower, which is especially required by the narrow right of way available. The same property, however, employs the horizontal plane design in mountain country where ice loads may be met. The design indicated at "GG" represents the type of tower used on a recent 220-kilovolt development in Pennsylvania and reflects the most con-

servative, as well as the most advanced, practice. Heavy test loadings, ample spacings and high working tension in the conductors are all taken care of by this construction, which probably represents the acme of the transmission line art down to the present time. Design "HH" is used on an extensive 110-kilovolt power system in the mountains of Chile, where severe weather conditions are met. Test loads on the normal suspension tower are based upon the failure of three wires in one span, and under the test loading the structure failed at from 30 to 100 per cent. in excess of the requirements.

The Colorado towers ("JJ") are of a type which is no longer perpetuated, although a very large tonnage of these towers was fabricated during the years 1908 and 1912. For light construction they were found economical, more especially on pin-type insulator lines, but with greater transverse loads a more complete system of bracing was found necessary.

Tower Specifications.—The great diversity of designs and requirements makes the matter of specifications a very important one in this instance. As an illustration of an important detail, it is sometimes specified that a suspension tower shall be designed for the failure of one "conductor," and at another time for one "wire." In the latter case it would be taken to mean a ground wire which, being at the apex of the structure, would lead to the maximum bending moment and uplift. On the other hand, unless installed at the end of a crossarm, there would be no torsion load on the structure. It is, above all things, necessary for the test loads to be specific, and the schedule which follows affords a reasonably satisfactory specification as issued by an extensive power system in Australia. (See example T, Table 36.)

Specification of Apparatus

(1) *Steel Transmission Line Towers.*—The steel towers covered by this specification are to be used to support insulators, conductors, and ground wire for a 112-mile transmission system operating at 132,000 volts.

The suspension and strain towers shall be designed to support six steel-cored aluminum line conductors, and the terminal towers three steel-cored aluminum line conductors. Each conductor will have a cross-sectional area of approximately 0.316 square inch, and will be composed of seven strands of double galvanized plough-steel wire and thirty strands of aluminum wire, each strand having a diameter of 0.1155 inch. The weight of the conductor per 1,000 feet will be 640 lb. There will also be one Siemens-Martin steel ground cable having a diameter of ½ inch.

Each line conductor will be hung from suspension insulators below the crossarms, the length of the string of insulators being taken as 4 feet.

The design of the towers shall be such that, when any string of insulators is swung to an angle of 60 degrees with the vertical, the conductor attached thereto cannot come to within 4 feet of any part of the tower.

The suspension and strain towers are to be arranged to accommodate two sets of three conductors, one set on each side of the tower, and the conductors of each set are to be placed in a vertical plane and spaced 10 feet apart.

The terminal towers are to be arranged to accommodate one set of three conductors spaced in a horizontal plane 16 feet apart.

A ground wire is to be hung without insulators on the top of each tower at least 7 feet from any conductor.

(2) *Height of Towers.*—The towers shall be so designed that the lowest conductor support shall be 42 feet from the ground line in the case of the suspension type, and 40 feet from the ground in the case of the strain and terminal type.

(3) *Spacing.*—The normal spacing of the towers on level ground shall be 1,056 feet, giving the conductors a sag of 15 feet at 160° F.

(4) *Strength of Towers.*—The towers shall be designed to withstand the following loads:

(A) Suspension towers.

(1) Vertical load, 1,000 lb. at each of the seven points of cable attachment; total, 7,000 lb.

(2) Horizontal pull, in the direction of the line, of 5,000 lb. at any one point of attachment.

(3) Horizontal load, transverse to the line, of 1,000 lb. at each point of attachment; total, 7,000 lb.

(4) Wind pressure on tower of 20 lb. per square foot on one and a half times projected area of one face of the tower.

(5) Dead load of tower.

(6) Combine all loads.

(B) Strain towers used at all dead-end points and at angle points where change in direction of the line does not exceed 45 degrees.

(1) Vertical load, 1,000 lb. at each of the seven points of cable attachment; total, 7,000 lb.

(2) Horizontal pull in direction of the line, 9,500 lb. at each point in any selection of the seven points of attachment, all in one direction; maximum total, 66,500 lb. Each crossarm shall be designed for the whole unbalanced pull of 12,000 lb.

(3) Horizontal load, transverse to line, 9,500 lb. at each point in any selection of the seven points of attachment, all in one direction; maximum total, 66,500 lb.

(4) Wind pressure on tower of 20 lb. per square foot on one and a half times projected area of one face of the tower.

(5) Dead load of tower.

(6) Combine all loads.

(C) Terminal towers used at both ends of line.

(1) Vertical load of 1,000 lb. at each of the four points of attachment; total, 4,000 lb.

(2) Horizontal pull in direction of the line of 9,500 lb. at each of the four points of attachment; total, 38,000 lb.

(3) Horizontal load, transverse to the line, of 1,000 lb. at each point of attachment; total, 4,000 lb.

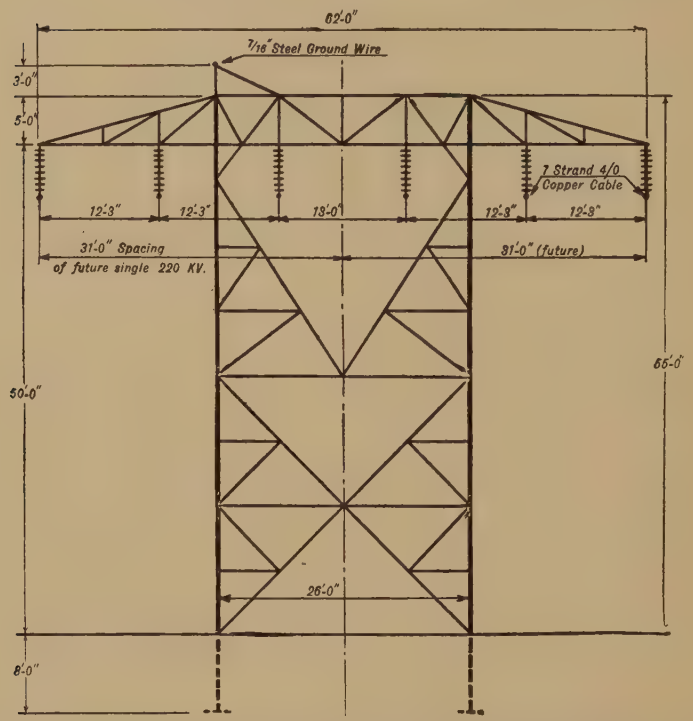

FIG. 75.—Single-circuit tower carrying two 110-kilovolt circuits in horizontal plane (designed for ultimate use with one 220-kilovolt circuit).

(4) Wind pressure on tower of 20 lb. per square foot on one and a half times projected area of one face of the tower.

(5) Dead load of tower.

(6) Combine all loads.

(5) *Unit Stresses.*—The following unit stresses shall not be exceeded in the design of the towers.

	Per sq. in.
Tension on net section	20,000
Compression on gross section	20,000–85 L/R
Shear on bolts	13,500
Bearing on bolts	27,000

where "L" is the unsupported length of the member and "R" is the least radius of gyration, both in inches.

(6) *Ultimate Strength.*—The ultimate strength of the steel used in the manufacture of these towers shall not be less than 62,700 lb. per square inch, with an elongation of not less than 20 per cent. on a gauge length of 8 inches.

(7) *Climatic Conditions.*—The climatic conditions prevalent in the district are as follows:

Maximum indicated wind velocity	108 miles per hour.
Minimum temperature	20° F.
Maximum temperature	160° F.
Sleet	None.
Snow	None.
Fog and lightning	Infrequent.

(8) *Details of Design—Open Sections.*—The structure shall be so designed that all parts shall be accessible for inspection and cleaning.

(9) *Pockets.*—Pockets or depressions likely to hold water shall have drain holes.

(10) *Splices.*—Where a lap splice is used in leg angles the back of the inside angle shall be chambered to clear the fillet of the outside angle.

(11) *Bolts and Nuts.*—All connections shall be made by means of bolts and nuts, the minimum size of which shall be $\frac{5}{8}$-inch diameter. The bolts connecting the different parts of the tower together shall be of as few different lengths as practicable. The unthreaded portion of the shank of each bolt shall be at least as long as the combined thicknesses of the several members to be bolted together. Each bolt shall be provided with a spring washer.

(12) *Bolt Holes.*—All bolt holes shall be punched before galvanizing, and shall not be more than $\frac{1}{16}$ inch larger than the diameter of the bolt.

(13) *Duplication of Parts.*—In the case of square towers, all four faces shall be made alike as nearly as practicable.

(14) *Minimum Number of Parts.*—Preference will be given to the design that has the least number of parts.

(15) *Minimum Thickness.*—The minimum thickness of material in the legs shall be ¼ inch, and that for any other member having calculated stresses shall be 3/16 inch.

(16) *Ratio of Slenderness.*—In compression members the ratio of the unsupported length divided by its least radius of gyration shall not exceed the following:

Legs	140
All other members having calculated stresses	200
Members having nominal stresses only	220

(17) *Use of Rods.*—Rods will be allowed only where proper provision is made for tightening up same in the field.

(18) *Ground Wire Clamp.*—The ground wire clamp shall be considered a part of the tower, and shall be furnished with same. It shall be of such design as will firmly hold, but not injure, the cable.

(19) *Insulator Connections.*—The contractor for the towers shall provide the necessary bolts and holes in the steel work of the towers for the connection of the insulators.

(20) *Ladder.*—At least one leg of the tower shall be provided with steps. These steps shall be at least ⅝ inch in diameter and not more than 16-inch centers, starting 8 feet from the ground.

(21) *Galvanized Work.*—All parts of the structure, except threaded portions, shall be galvanized by the hot process after all punching, cutting and other machine work is completed. All threaded parts shall be sherardized. The galvanizing shall consist of a coating of zinc of uniform thickness, so applied that it will adhere firmly to the surface of the steel. Any specimen selected by the engineer shall be capable of withstanding the following test:

It shall be immersed in a standard solution of copper sulphate for one minute, and then removed, immediately washed, and thoroughly wiped and dried. This process shall be repeated several times, and if after the fourth test there shall be a copper-coated deposit on the sample, or the zinc should have been re-

moved, the lot from which the sample was taken shall be rejected. The solution shall consist of commercial copper-sulphate crystals in water, having a specific gravity of 1.185 at 70° F.

(22) *Material.*—The steel used shall be made by the open-hearth process, and conform to the latest specification for structural steel recognized as standard practice in the country in which the plant is manufactured.

(23) *Marking.*—Each separate member shall be plainly stamped with a number. All like parts shall have the same number, the mark being placed in the same relative position on each piece, but all different members shall have different numbers to distinguish them. This marking shall be stamped into the steel before galvanizing with numbers at least ¾ inch high, in such manner as to make them plainly visible after galvanizing.

(24) *Size and Weight of Packages.*—The towers are to be delivered in sections, and each section shall be of such size and weight as to readily permit of its assembly with the other sections in the field with bolts and nuts. They shall be delivered " knocked down " with similar members tied securely in bundles of approximately 100 lb. each. All parts that cannot be bundled, such as pins, bolts, washers, etc., shall be delivered in boxes and kegs in unit packages for each individual tower.

(25) *Foundations.*—The towers shall be designed with sufficiently large ground stubs to give stability in dry, sandy soil; no concrete foundations shall be necessary, except in a special case, such as swampy ground. It may be assumed that earth weighs 100 lb. per cubic foot, and that the base will engage the frustrum of an inverted pyramid of earth whose sides have an angle of 30 degrees with the vertical.

(26) *Tests.*—One of each type of tower shall be assembled and tested at the maker's works with loads as nearly as practicable like those for which the tower is designed, and one of each type of tower shall be tested to destruction. The members forming the test tower shall be selected at random from lots of

similar members. The towers to be tested shall be set on a rigid foundation. The whole of the expense incurred in these tests shall be borne by the contractor, and shall be carried out in the presence of the engineer, reasonable notice being given to the latter of the intention of the contractor to test.

(27) *Erection.*—The towers shall be so designed that after they have been assembled on the ground they can be raised to the vertical position without any of the members being strained or buckled.

(28) *Alternatives.*—Tenderers may submit alternatives of their standard design. They must, however, explain their proposals fully, and submit detailed drawings and particulars, together with information as to where similar designs have been used.

(29) *Packing and Marking.*—The plant for shipment or transportation shall be suitably packed for transit by sea or by rail, as the case may be. All packing on delivery shall become the property of the Commissioners. Each case shall be marked with the following brand:

CHAPTER IV

DESIGN

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Wind and Ice Loads.—The first and broadest object of design is the selection and adjustment of the materials of construction to withstand the conditions of load with a predetermined margin. The problem of effecting this object at the minimum cost is treated under the heading of " Economics."

Loading on the conductor wires, exclusive of their own weight, consists in wind pressure and ice load. Although the true effects of wind and ice loading are very far from being determinate, certain basic assumptions help to simplify the problem. Primarily it is assumed that the wave front of the wind is a vertical plane, and that the velocity applies to every part of the area under load. Ice or sleet is presumed to build up around the wires in a cylindrical form symmetrical throughout the entire span.

Wind velocity, as indicated by the anemometer readings, varies from zero to 100 miles per hour, but an indicated velocity of more than seventy is very rare. The corresponding corrected velocity is fifty-five miles per hour, which is approximately equivalent to 13 lb. per square foot pressure. This correction is necessary because anemometer figures relate to high altitudes, and velocities at the plane of a transmission line are distinctly lower. This pressure applies to a normal surface, and in cor-

recting for a cylinder must be reduced by about 33 to 40 per cent. A number of experiments have been made which justify this relation. It is obvious that the pressure on a projected cylindrical surface cannot be more than $\pi/4$ times that on a normal plane. Actually, the streamline diversion of wind currents reduces it to about 60 per cent. Eight lb. per square foot wind pressure probably forms the basic loading assumption for by far the greater part of the transmission line mileage built in the United States, and the same figure has been incorporated in the "Heavy" loading conditions specified by the National Electric Safety Code.

TABLE 38.—*Wind Loading.*

Weather conditions.	Velocity indicated. m.p.h.	Velocity corrected. m.p.h.	Pressure, lb. per sq. ft.	
			Wires.	Tower members.
Calm	10	9.5	—	—
Breeze	20	18	0.80	1.33
Wind	30	26	1.70	2.84
Strong wind	40	33.5	2.70	4.50
" "	50	40.5	4.10	6.84
Gale	60	47.5	5.75	9.58
"	70	54	7.40	12.30
Heavy gale	80	62	9.80	16.30

That the foregoing figures are subject to revision based on more complete experiment is indicated by several contributors to this subject. According to E. B. Wedmore and W. B. Woodhouse in a recent paper before the International High Tension Conference the formula as generally used

$$P = KAV^2$$

is incomplete (P being the pressure on unit area, K a constant, A the area opposed to wind, and V the wind velocity). "K" varies with the form and size of the surface considered. The main question is whether the formula as used is accurate within the limits of present-day practice, and it would seem that this is the case. New problems are arising, however, in connec-

tion with wireless aerials and towers of unprecedented altitude and exposure, and it is found necessary to use much more conservative design constants in such cases.

Design practice in Italy has been outlined by Gino Rebora, who quotes the following formulæ:

Wind load on conductor in kilograms per square meter,

$$P = 0.0045AV^2$$

(where A is the projected area $L \times d$).

For structural steel supports

$$P = 0.007AV^2\left(1 + \frac{A_0}{A_1}\right)$$

where P, A and V have the usual significance, and where A_0 represents the area of empty space in the structure, and A_1 is the gross area bounded by the outside perimeter. For conventional tower construction A_0/A_1 would be of the order of 0.85 to 0.95, whilst for steel pole practice of the type customary in Italy the ratio would be from 0.75 to 0.90. Using these formulæ the wind load on wire for a velocity of eighty miles per hour becomes 15 lb. per square foot of projected area, and on structural towers 47 lb. per square foot of the area of one side. In Britain and America it is customary to use an area one and a half times that of one side in the calculations of wind load on structures, but the resultant loadings are considerably less than those used by the Italian engineers because the wind velocity is taken at fifty instead of eighty miles per hour.

Ice or sleet forms the other important factor in loading. If rain falls at a time when the surface of the earth is very near the freezing point, it will congeal into ice, forming an adhesive coating which rapidly builds up in thickness. The unit weight of the ice coating is assumed at 57 lb. per cubic foot; it is also assumed to be cylindrical, but the tendency is for the ice to build up on the lee side of the wire, forming an elliptical section. Many other irregularities are noted if the deposit is partially snow and ice, and in such a case the thickness of coating may be

3 or 4 inches. Although the density of snow is very low it is quite adhesive, and greatly increases the windage of the conductor. Frozen fog deposits are also encountered at high altitude, and consist of a snow formation, not in the air, where it would be precipitated, but on the cold metal surfaces of wire and towers, usually building up on the weather side. Observations have shown this deposit to build up rapidly wherever it can find an anchorage, and although the density is only about one fifth that of solid ice, the great masses of frozen fog have sometimes proved very destructive.

While such forms of deposit are difficult to define, a uniform radial thickness of sleet is commonly assumed for wires of all sizes; as a consequence, the calculated as well as the actual ice load is far more significant upon the smaller wires both in respect to weight and additional windage. In certain of the German rules for overhead construction assumption has been made of an ice coating varying with the size of the wire, but this variation is distinctly not justified by the observed facts. It is true that design becomes very difficult with conductors of 0.05 square inch copper, or less, if a ½-inch ice load is assumed, but this provides encouragement for the developing of a higher tensile strength conductor which will yield economical construction as well as safe operation. In the rules of the British Electricity Commissioners, ½-inch ice coating is assumed for high-tension wires and ¼ inch for lower voltage. This, again, is open to criticism, because ice formation is a function of latitude and exposure; it has no relation to the electrical features of the system. If, as seems probable, the intention is to reserve a higher grade of construction for the higher voltage, the change should have been made in the factor of safety rather than in the loading assumptions, which latter properly regarded are constant.

In the United States considerable diversity has existed in the selection of design loads, and the attempt has been made to standardize them in the National Electric Safety Code. Recognizing the vast disparity in climatic conditions, the country has

been divided into three sections, for which respectively (*a*) heavy, (*b*) medium, and (*c*) light loadings are specified. It should be noted that the heavy loading applies to 80 per cent. of the total territory.

Details of the loadings are as follows:

TABLE 39.—*Wind and Ice Loads on Wire (National Electric Safety Code).*

(A) Heavy loading.....	One half inch ice coating with a wind pressure of 8 lb. per sq. ft. on the projected surface of the ice-covered wire at 0° F.
* (B) Medium loading.....	Two thirds the resultant of the "heavy" loading at 15° F.
* (C) Light loading.....	Two thirds the resultant of the "medium" loading at 30° F.

* The Medium and Light loadings in the Code are at present under revision.

For each of the above conditions the stress in the conductors shall not exceed one half the ultimate strength. It should be intimated that in American practice no special code of construction is obligatory, the matters of design loading and safety factor being left to the engineers concerned. However, in the case of crossings of railroads, telephone lines, or other interests, certain more or less rigid standards must be met, and upon these standards the more conservative type of construction is based. It is particularly noteworthy that in respect of wind and ice loading the National Electric Safety Code and the rules of the British Electricity Commissioners are in agreement.

Although ½-inch ice coating represents the "heavy" loading above specified, it must not be thought that this is the maximum desirable design assumption. On several power systems in Canada, ¾-inch ice thickness is found to be a necessary assumption. Further, in a statement * on the mechanical design of 220-kilovolt transmission systems, A. E. Silver has assumed 1½ inches radial thickness of ice on all the wires, together with the customary 8 lb. per square foot wind load.

> "It is not believed that there is any reasonable likelihood of the line being subjected to such a simultaneous

* *Transactions A.I.E.E.*, vol. 38, p. 1044.

combination of conditions. From the standpoint of vertical tower loads there is a real possibility of occasional ice loadings as heavy as or even heavier than assumed, and accordingly a reasonable margin of excess vertical strength is called for. Justification for these apparently extreme loading assumptions is found in the high service standards which, as noted, must in general apply in 220-kilovolt service. In view of the economic importance of continuity of service, it is considered that this basis is not unreasonable for a region where severe climatic conditions obtain, and in particular, where heavy sleet is to be expected."

Some information has been contributed by W. Borgquist and J. Nordell on the revised design assumptions adopted for heavy line construction in Sweden. Three grades of loading are assumed for more or less severe climatic conditions, and the radial ice thickness is respectively 1¾, 1½, and 1⅛ inches, with a wind loading of 5 lb. per square foot on the projected area. These engineers also tabulate a series of lighter ice loadings applicable to line construction of a lower grade. In this case also it would seem more logical to have standardized the external loads and to have safety factors for different types of construction.

In Japan a very extensive mileage of high-tension line has been built under designs based on Government specifications for loading. The respective loadings have been made public by Dr. Shibusawa, of the Department of Communications, as follows:

TABLE 40.—*Japanese Rules for Loading.*

(*a*) Wind load on poles	24 lb. per sq. ft.
(*b*) Wind load on wires	20 lb. per sq. ft.
(In each case the projected surface is assumed.)	
(*c*) Wind load on flat surfaces	40 lb. per sq. ft.

For specified districts where snow and ice are experienced a radial thickness of ¼ inch is assumed; at the same time, the foregoing wind pressures are reduced 50 per cent. It is presumed that heavy gales are not coincident with sleet loading,

and this is true for Japan, because the typhoon season is in September, preceding the first snowfall by about two months. For the above loads a safety factor of two is specified, assuming tensile strength of copper wire to be 50,000 lb., and aluminum 23,000 lb., per square inch.

This problem of sleet formation and methods of preventing it has been studied very thoroughly by the engineers of the Pennsylvania Water and Power Co., and R. L. Thomas of this system has recorded the procedure. There are normally four circuits operating on the forty-mile line from the Susquehanna River to Baltimore. If the load will permit, on receipt of a warning that a sleet storm is impending, one circuit is cut out, short-circuited at the receiving end, and connected to the low-tension bus at the power station. A current of 390 amperes is found sufficient; in fact, 300 amperes will prevent ice formation. When the lines are under load, the requisite current losses are made up by under-exciting the receiving plant so as to reduce the power factor and increase the line drop. It is believed that no future large transmission systems will be constructed in exposed terrain without special provision for melting ice being made and allowed for.

Before any subsequent calculations can be made, it is necessary to estimate the weight of ice and the wind pressure per unit length of wire and to combine the horizontal wind with the vertical weights of wire and ice, and so derive the resultant maximum load. This provides the starting point for computing the sag and tension in the line under various conditions. In the conventional nomenclature—

w = weight of wire in pounds per foot.
i = weight of ice coating in pounds per foot.
W = total vertical load : $w + i$.
P = wind load on projected surface of wire and ice in pounds per foot.
= total horizontal load.
R = total resultant load : $\sqrt{W^2 + P^2}$.
σ = loading ratio : $\frac{R}{W}$.

The loading ratio will be found a most important quantity in subsequent calculations.

Another significant quantity is the angle to which the conductor will swing when under maximum loading. Obviously the ratio of horizontal to vertical loads is the tangent of the angle which the conductor will make with the vertical plane; hence

$$\text{angle } \theta = \tan^{-1} \frac{P}{W}$$

With light conductor wires the swing will be quite considerable and although experience shows in general a synchronism between the cables on a given span, a very small difference in tension or a stiff insulator string may disturb this. Some account of the angle of swing must, therefore, be taken in the spacing.

Wire Tension.—Under the most severe loading, as already defined, the maximum mechanical tension will be exerted on the line wires. This quantity depends upon—

(*a*) The ultimate strength of the conductors; and
(*b*) The factor of safety employed.

Although it was once customary to specify that the maximum working tension should not exceed one fifth the ultimate figure, it is now usual to raise the proportion to one half, reducing the factor of safety from five to two. This last figure is embodied in the National Electric Safety Code in the United States as well as in construction codes of other countries where transmission line design is in an advanced stage. In case this change should be criticized, it is pertinent to point out the essential difference between a flexible wire span and a rigid structure, such as a bridge. In the case of the latter, if the design were carried out with a factor of two, and if in some abnormal conditions double the design load were imposed upon the structure, it would assuredly fail and become a wreck. A similar abnormal load placed upon a wire span will have a totally different effect. Every additional degree of load will give an elastic stretch to the wire, leading to an appreciable increase in the

TABLE 41.—*Loading on Copper Conductors. National Electric Safety Code.*

(Calculated for one half inch ice coating and a wind pressure of 8 lb. per square foot projected area.)

Size. Circular mils.	Stranding.	Diameter of cable. Ins.	Weight per foot. Lb.	Weight ice per foot. Lb.	Total weight. Lb.	Diameter including ice. Ins.	Wind load per foot. Lb.	Resultant load per foot. Lb.	Loading ratio.
1,000,000	61 × 0.1280	1.152	3.09	1.035	4.125	2.152	1.435	4.350	1.41
900,000	61 × 0.1215	1.093	2.78	0.983	3.763	2.093	1.395	4.012	1.45
800,000	61 × 0.1145	1.030	2.47	0.945	3.415	2.030	1.353	3.670	1.48
700,000	61 × 0.1071	0.964	2.16	0.905	3.065	1.964	1.308	3.330	1.54
600,000	37 × 0.1273	0.891	1.85	0.860	2.710	1.891	1.260	2.980	1.61
500,000	37 × 0.1162	0.813	1.54	0.810	2.350	1.813	1.209	2.640	1.72
400,000	19 × 0.1451	0.725	1.24	0.766	1.990	1.725	1.145	2.295	1.85
300,000	19 × 0.1257	0.628	0.926	0.690	1.616	1.628	1.084	1.944	2.10
212,000	$\frac{19}{7}$ × 0.1055	0.527	0.653	0.629	1.282	1.527	1.018	1.632	2.49
168,000	$\frac{19}{7}$ × 0.094	0.470	0.518	0.588	1.106	1.470	0.975	1.470	2.84
133,000	7 × 0.1380	0.414	0.411	0.554	0.965	1.414	0.941	1.345	3.27
106,000	7 × 0.1228	0.369	0.326	0.527	0.853	1.369	0.910	1.245	3.82
83,700	7 × 0.1093	0.327	0.258	0.503	0.761	1.327	0.883	1.164	4.50

TABLE 42.—*Loading on Aluminum-Steel Conductors. National Electric Safety Code.*

(Calculated for one half inch ice coating and a wind pressure of 8 lb. per square foot projected area.)

Size. Circular Mils.	Stranding.		Diameter of cable. Ins.	Weight per foot. Lb.	Weight ice per foot. Lb.	Total weight per foot. Lb.	Wind load per foot. Lb.	Resultant load per foot. Lb.	Loading ratio.
	Aluminum.	Steel.							
1,000,000	54 × 0.136	7 × 0.136	1.224	1.290	1.080	2.370	1.480	2.79	2.16
900,000	54 × 0.129	7 × 0.129	1.161	1.160	1.035	2.195	1.440	2.62	2.26
800,000	54 × 0.122	7 × 0.122	1.098	1.030	0.995	2.025	1.400	2.46	2.39
700,000	54 × 0.114	7 × 0.114	1.026	0.902	0.949	1.851	1.348	2.28	2.53
600,000	54 × 0.105	7 × 0.105	0.945	0.775	0.905	1.680	1.294	2.12	2.74
500,000	30 × 0.129	7 × 0.129	0.903	0.785	0.876	1.661	1.268	2.09	2.66
400,000	30 × 0.115	7 × 0.115	0.805	0.627	0.814	1.441	1.202	1.88	3.00
300,000	30 × 0.100	7 × 0.100	0.700	0.471	0.749	1.220	1.131	1.67	3.54
212,000	6 × 0.188	7 × 0.063	0.564	0.273	0.666	0.939	1.042	1.40	5.14
168,000	6 × 0.167	7 × 0.056	0.501	0.216	0.625	0.841	1.000	1.31	6.07
133,000	6 × 0.149	1 × 0.149	0.447	0.186	0.590	0.776	0.964	1.24	6.67
106,000	6 × 0.133	1 × 0.133	0.399	0.149	0.560	0.709	0.931	1.17	7.85
83,700	6 × 0.118	1 × 0.118	0.354	0.117	0.532	0.649	0.902	1.11	9.50

sag. But the sag and the tension are reciprocals, and increase in the first with constant loading diminishes the second. Or, if the load be increased by reason of heavy ice and wind, the sag will be simultaneously increased with but a very slight additional tension. It is true that, if the loading is exceedingly heavy (in excess of the usual design assumptions of ½ inch ice and 8 lb. wind), then the elastic stretch will be entirely absorbed, the yield point will be passed, and the wires will take a permanent set and an appreciably increased sag. Under the worst conditions this may make it necessary to restring part of the line. The noteworthy fact is that under none of these circumstances does the wire fail in the sense that a structure fails, because in the wire the stress is not proportional to the loading, whereas in the structure it is, and the conclusion is that the nominal "safety factor" may, with entire prudence, be distinctly lower.

Experience with high-tension lines in many parts of the world leads to the conclusion that a wire very seldom parts under excess loading. When failure occurs it is usually due to (*a*) an insulator or tension-eye fracture; (*b*) a pole or tower crossarm deforming; (*c*) a wire burning off due to short circuit caused by unequally loaded wires swinging together; (*d*) an insulator flashover, which burns off the wire before the arc can be suppressed. The appropriate precaution in each case is obvious, but the present tendency is to increase the safety of operation by permitting the line wires to absorb abnormal mechanical loads without transmitting them to the structures. This is effected by the almost universal use of suspension insulators, careful elimination of angles and dead-end points as well as points of uplift, and the employment of weights to control insulator deflection.

Whilst a maximum tension of approximately the elastic limit or one half the ultimate stress is, therefore, permissible, it does not follow that it is always expedient. With modern transmission lines very large and heavy cables are coming into use, and the adoption of a design tension of one half the ultimate necessarily leads to very heavy test loads on the towers. Con-

struction costs may often be reduced by stringing for a maximum tension of 40 or 30 per cent. of the ultimate value, especially with conductors of high tenacity, such as aluminum-steel with thirty-seven wires. Every design must, of course, be worked out upon its own merits, but where the size of wire exceeds 300,000 c.m. copper or its equivalent this reasoning will oftentimes be found applicable. When cables are large and heavy, an increased tension does not lead to so perceptible a reduction in the sag as in the case of smaller wires, and it leads to higher cost in respect of clamps and insulators throughout the line. In practice, it is found desirable to divide the line into sections and to string each section with the appropriate tension, depending upon the loading likely to be experienced, the profile, and the spans and clearances. In any event, should the normal maximum tension exceed 5,000 lb., a careful study of the constants is merited to determine whether a relaxation of this value might not result in greater economy. In this connection W. Dreyer, referring to the construction of 220-kilovolt lines of the Pacific Gas and Electric Co. in California, writes as follows: *

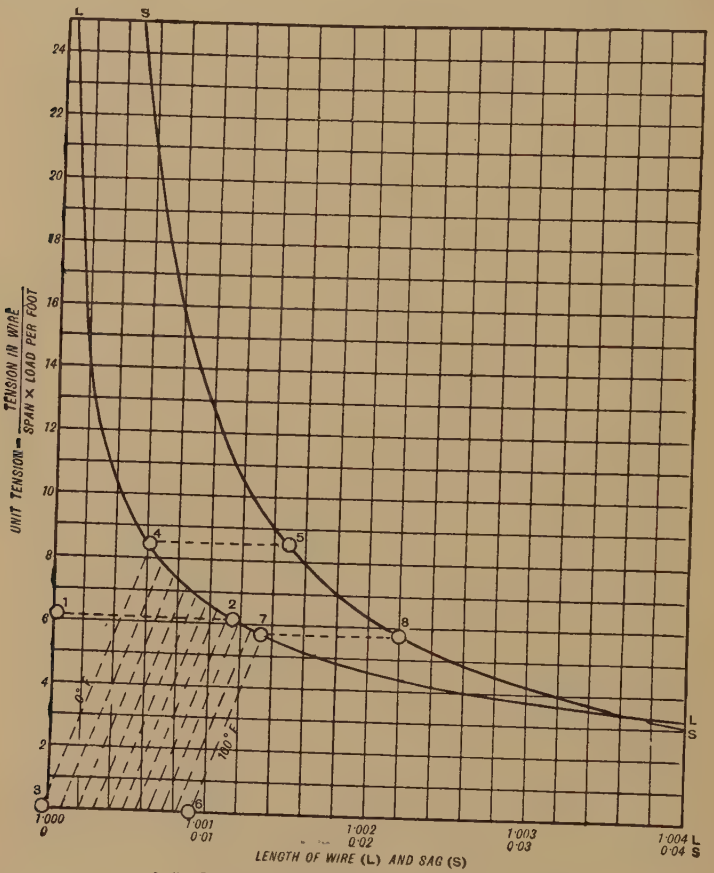
> "The usual practice in tower line construction is to string the conductor so that it will be stressed nearly to its elastic limit when under maximum loading. The writer believes that following this practice blindly will give neither the most economical nor the most satisfactory transmission line. Investigations have been made by our Company to determine the conductor stress which would result in the lowest cost for supporting structures, consideration being given to both the towers and their foundations. This investigation showed that a maximum tension of 17,000 lb. per square inch (30 per cent. ultimate strength) for copper of 250,000 to 500,000 circular mils. resulted in the lowest cost of the completed line. The use of this tension instead of 27,000 lb. per square inch resulted in a saving of about 20 per cent. in the cost of

* *Transactions A.I.E.E.*, v. 42, p. 962.

towers and foundations. For the Pit River 220-kilovolt line, this represents a saving of nearly $1,200 per mile. In addition, this tension, which is only about 60 per cent. of the elastic limit of medium drawn copper, greatly reduces the load on dead-end insulator strings, consequently reduces the number of dead-end insulator failures, and therefore gives a more satisfactory line."

Sag Calculations.—The assumption is commonly made that a transmission wire suspended between two supports follows the curve of the catenary. Calculations are based upon a given maximum unit tension in the conductor, together with the standard values of external loading, from which can be derived the sag or deflection at the lowest point, the necessary clearances, desirable span length, and height of supports. Since the calculation of sag forms the basis for such an important series of operations, it is essential that an accurate method be used. A statement is sometimes made that the parabola represents the curve of a suspended wire "with sufficient accuracy." This is by no means true, especially where the spans are sometimes 800 feet or more. Errors are introduced which may lead to seriously impaired clearances when the line comes to be constructed, and even to accidental short circuits during operation. Such a happening will cost a great deal more than the extra time spent in making preliminary calculations by a more accurate method. It is sometimes argued that the construction crew cannot work to closer than 10 per cent. accuracy, and that preparation of tables and curves to a more proximate degree is a waste of effort. At the present time, however, a very great amount of care is exercised in stringing transmission wire; the crews are provided with thermometers and wind gauges, whilst sags are read from a theodolite. Dynamometers are calibrated for use as a check when the wires are dead ended. In any event, it is not fair to issue inaccurate data to a construction crew in view of their obvious limitations. The better plan is to supply them with the best figures possible, with instructions to work as closely to them as conditions will permit.

Analysis of the line-wire catenary, with the necessary modifications for elasticity and thermal expansion, has been performed by many investigators, and it is unnecessary to add anything to the mathematics of the subject. The usual plan in office calculations is to employ simply two elementary curves on a large scale which embody the fundamental catenary relations,



1	Unit Tension for Copper Conductor 0·2 sq. in. on 400 foot span	6·10
2	Length of wire (per foot) maximum stress and load	1·00115
3	" " " " zero stress	·99995
4	Unit Tension with wind and ice loads relieved at 0°F	8·5
5	Sag of wire " " " " " " " "	·075
6	Length of wire with zero stress at 100°F	1·00091
7	Unit Tension with wind and ice relieved at 100°F	5·7
8	Sag of Wire " " " " " " "	·022

FIG. 76.—Universal catenary chart, showing relation between length of unit wire, sag and unit tension in wire with practical example.

and to use the slide rule for deducing the required quantities. Instead of plotting the relations of length of wire, tension and sag for every possible combination of size, material, weight, loading and span, let an elementary wire be considered. This wire will be strung on a span of 1 foot (with supports at the same elevation) and have a weight of 1 lb. The tension is supposed to be varied between maximum practical limits. Lengths and sags read from these elementary curves can be multiplied up by the factors actually in use.

The property of the catenary, which is here developed in the manner devised some years ago by Percy H. Thomas,* is constant shape of the curve, with variation of the factors. A wire, when suspended with a load on any particular span, will have a definite and distinct sag and shape of curve. Reducing the load to 1 lb. and the span to 1 foot, the form of curve remains unchanged, and consequently the sag, expressed as a percentage of the span length, is unaltered.

In practice, the values of L, the wire length, and D, the sag at mid-span, are plotted against what is called the "unit tension." This quantity is equal to

$$\frac{\text{Maximum tension in wire}}{\text{Span} \times \text{Load}}$$

The tension is in pounds; the span in feet; and the load (or what has been referred to as the resultant loading) in pounds per foot of wire. These foregoing relations have been calculated out by expansion of the hyperbolic series, and the result is set out in the following table:

In many engineering offices graphical methods are preferred to those involving mathematical analysis because they are more readily understood and checked. A reduced form of the chart used by Thomas is shown in Fig. 76 and it will be seen that the accuracy is dependent simply upon the scale to which the chart is drawn. In practical work this is made as large as convenient

* *Transactions A.I.E.E.*, 1911, p. 2229.

and the curves designed to cover a relatively limited range of wire sizes.

TABLE 43.—*Constants for Plotting Catenary Chart for Unit Wire on Unit Span.*

Unit tension.	Length.	Sag.	Unit tension.	Length.	Sag.
50	1.000,017	0.00250	4.573	1.002,017	0.02753
40	1.000,026	0.00313	4.196	1.002,402	0.03004
35.72	1.000,033	0.00350	3.878	1.002,819	0.03255
29.42	1.000,048	0.00425	3.606	1.003,040	0.03506
25	1.000,067	0.00500	3.371	1.003,754	0.03757
20.01	1.000,104	0.00625	2.550	1.006,680	0.05017
17.86	1.000,131	0.00700	2.328	1.008,086	0.05522
14.71	1.000,193	0.00850	2.063	1.010,444	0.06283
12.51	1.000,267	0.01000	1.919	1.012,194	0.06791
10.01	1.000,368	0.01175	1.742	1.015,068	0.07556
7.708	1.000,704	0.01626	1.643	1.017,154	0.08068
7.160	1.000,817	0.01751	1.517	1.020,542	0.08840
6.270	1.001,066	0.02001	1.445	1.022,973	0.09356
5.578	1.001,351	0.02252	1.315	1.026,881	0.10134
5.025	1.001,668	0.02502	1.297	1.042,190	0.10655
4.788	1.001,839	0.02627	1.050	1.051,190	0.14100

High values of unit tension relate to heavy wires on short spans, and low values to lighter wires on long spans; in practice, therefore, it will promote accuracy if several charts be drawn, each covering a limited range. In using the curves illustrated (Fig. 76) the procedure is as follows:

(1) Ascertain the appropriate unit tension by reference to the size and loading of wire, the desired maximum tension, and the length of span. Draw a horizontal reference line R through this value.

(2) The point where the reference line intersects the "length" curve is L, the length of wire with maximum loading, *i.e.*, with full wind and ice load.

(3) The point where the same line intersects the "sag" curve is D, the sag under the same conditions.

(4) Subtract from L the stretch of the wire λ. This elastic stretch is, by Hookes' law, S/E, where S is the full working stress and E is the modulus of elasticity, both in pounds per square inch. This operation $L - \lambda$ yields the unstressed length L_o. (Observe that L_o is sometimes less than unity.)

(5) Derive L_1; the actual length of wire without wind or ice, but loaded simply with its own weight, $L_1 = L_o + (\lambda/\sigma)$.

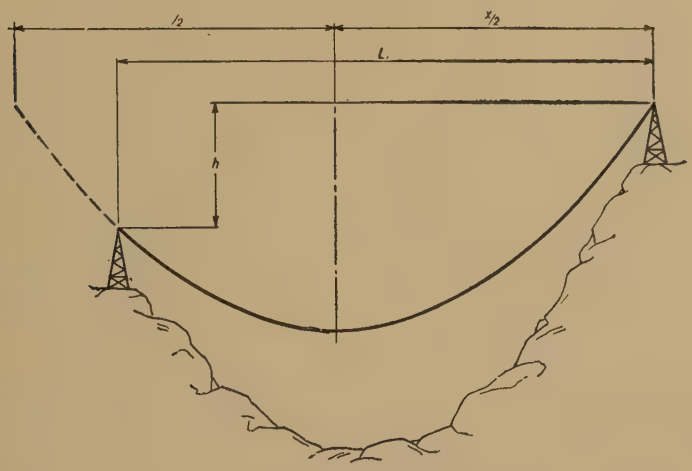


FIG. 77.—Notation for calculating sag with unequal height of supports.

As mentioned on p. 181, the symbol σ represents the ratio resultant loading: weight. The object is to add to L_o merely the amount of stretch due to the weight of the suspended wire itself. Set off the value of L_1 on the reference line (R).

(6) Obtain corrected value of L_1 by drawing from L_o on the base line through L_1 just located and producing to the length curve L. This is the true value of L_1.

(7) Draw a horizontal reference line (R_2) through the point just defined. Where it intersects the sag curve gives the sag value when all external load is removed from the wire. Where it intersects the unit tension axis gives a new unit tension and (by calculation) the actual tension.

(8) Add to L_o on the base line the extension due to the maximum temperature range, $L_1 = L_o(1 + \alpha t)$.

(9) From L_t draw a line parallel to L_oL_1 to intersect the L curve. Draw a horizontal reference line, and read sag and tension at $t°$. By subdividing the base between L_o and L_t into suitable temperature grades a series of parallels can be drawn

corresponding to intermediate temperatures. Horizontal reference lines will yield tension and sag values from which stringing curves may be drawn by plotting a series of isothermal tension and sag curves against a base of span length as illustrated. (Figs. 78–80.)

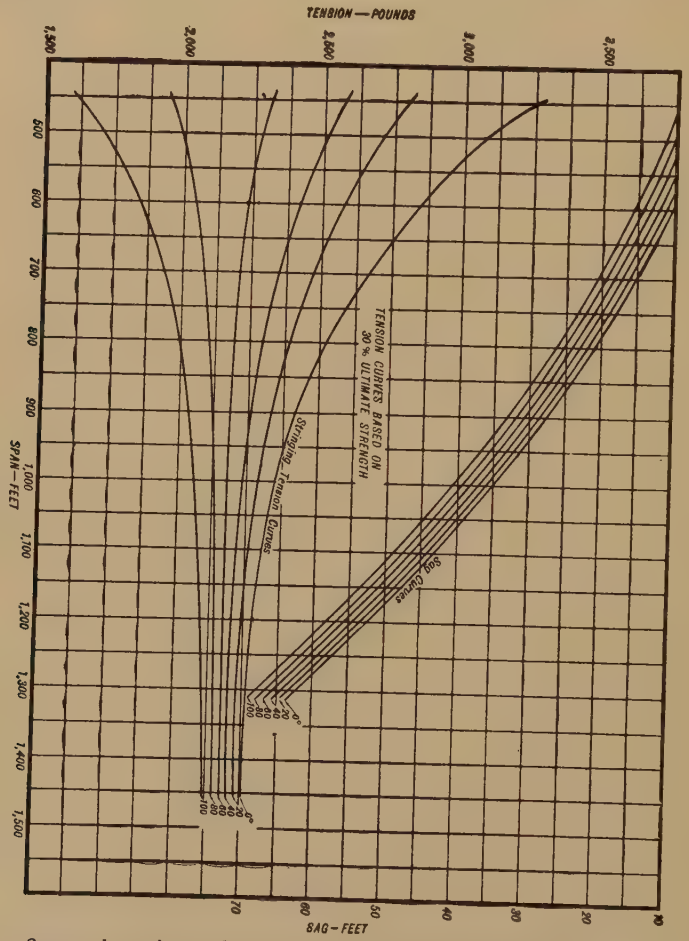


FIG. 78.—Sag and tension values for an aluminum-steel conductor, 415,000 cir. mils., with a maximum stress 30 per cent. ultimate strength.

In all the foregoing analysis it is assumed that the supports are on the same level. Where a difference in level exists it is necessary to derive the "equivalent span." It is assumed that

the wire as strung forms part of a catenary, the complete shape being represented by producing the curve past the lower support until it reaches the horizontal plane of the upper one. This represents the equivalent span, and calculations are based upon it in the conventional way.

The method is

$$x_1 = \frac{L}{2} + \frac{hT_1}{L}$$

where

x_1 = one half the equivalent span, *i.e.*, the horizontal distance from the upper support to the lowest point of the wire.
L = horizontal span as strung.
h = vertical distance between the planes of support.
T_1 = tension on the wire with unit loading of 1 lb. per foot.
$= \frac{T}{R} = \frac{\text{Actual maximum tension in pounds}}{\text{Loading in pounds per foot}}$

The example on page 194 illustrates a good and systematic way of deriving and setting out a complete series of sags and tensions for a wide range of spans and for temperatures ranging over 100° F. This method of setting out the work and proceeding step by step in reading from the catenary chart not only saves time, but it renders errors easily discernible.

While the Thomas method affords by far the best compromise of speed and accuracy for the average worker in this subject there are certain occasions where a greater degree of precision is required than a graphic method can yield. An analytical method of deriving sags and tensions based on the catenary law has been developed and published by James S. Martin of the Duquesne Light and Power Co. This author has compiled a table of catenary functions carried to seven significant figures by the use of which any routine problem involving the mechanical characteristics of a wire span can be solved by calculation. For which a calculating machine is recommended as a great time saver especially where economic comparisons have to be made between a number of alternative conductor materials and sizes.

A further valuable contribution to the mathematics of the subject has been made by Professor Geo. S. Smith of the Uni-

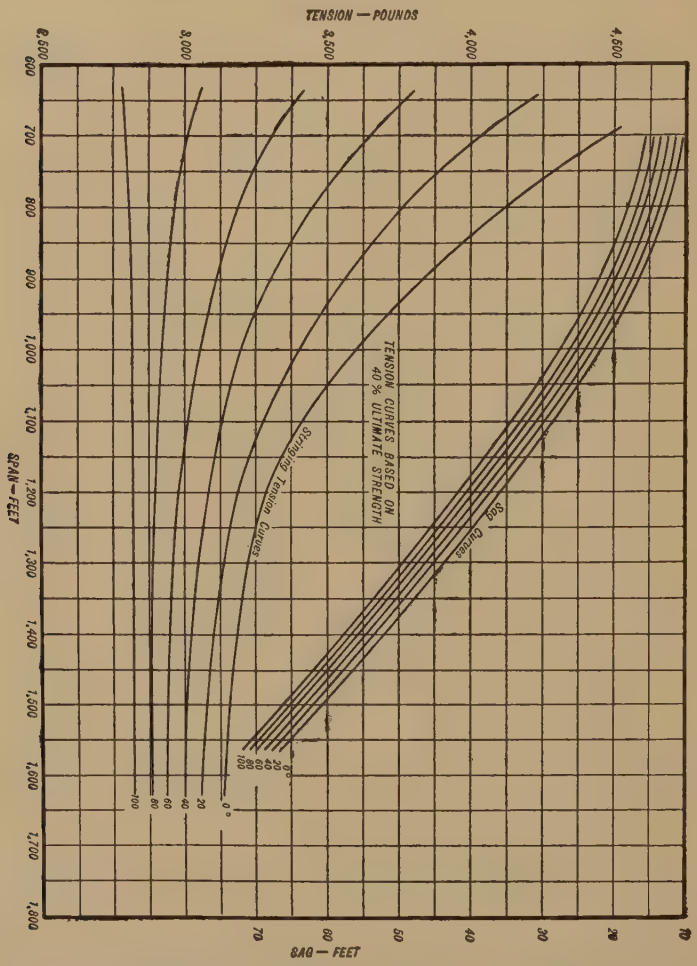


FIG. 79.—Sag and tension values for an aluminum-steel conductor 415,000 cir. mils., with a maximum stress 40 per cent. ultimate strength.

versity of Washington who has shown the application of the catenary equations to the solution of an extremely long span having supports at unequal heights.

Sag Calculations.

Conductor	Copper	0.20 sq. in.
"	"	255,000 cir. mils.
Stranding		37×0.083 or 7×0.193
Diameter of cable		0.581 in.
Weight per foot	(w)	0.780 lb.
Total load per foot	(R)	1.790 lb.
Ratio R/w	(σ)	2.30
Maximum tension		4,320 lb.
Modulus of elasticity	(E)	18×10^6 lb. sq. in.
Specific extension	(λ)	0.00120
Expansion coefficient	(α)	9.6×10^{-6}
Temperature range	(t)	100° F.

TABLE 44.—*Sag Calculations.* 255,000 *c.m. Copper.*
(From catenary chart, Fig. 76.)

Span (ft.)		400	600	800	1,000	1,200
Unit tension		6.10	4.05	3.04	2.43	2.02
L (from chart)		1.00115	1.00250	1.00470	1.00750	1.01150
L_0 $(L - \lambda)$		0.99995	1.00130	1.00350	1.00630	1.01030
$L_1\left(L_0 + \frac{\lambda}{\sigma}\right)$		1.00047	1.00182	1.00402	1.00682	1.01082
Unit tension$_2$		8.50	4.65	3.25	2.50	2.06
L $(L_0(1 + at))$		1.00091	1.00226	1.00446	1.00726	1.01126
at		0.00096	0.00096	0.00096	0.00096	0.00096
0°	Sag (ft.)	6	16.2	31.6	51	75
	Tension (lb.)	2,640	2,200	2,030	1,950	1,930
20°	Sag (ft.)	6.6	16.8	32.3	51.6	75.6
	Tension (lb.)	2,340	2,080	1,990	1,930	1,914
40°	Sag (ft.)	7.15	17.4	33.0	52.2	76.2
	Tension (lb.)	2,200	2,020	1,954	1,910	1,898
60°	Sag (ft.)	7.70	18.0	33.7	52.8	76.8
	Tension (lb.)	2,040	1,960	1,917	1,890	1,882
80°	Sag (ft.)	8.20	18.7	34.3	53.4	77.4
	Tension (lb.)	1,910	1,880	1,880	1,870	1,866
100°	Sag (ft.)	8.80	19.5	35.0	54	78.0
	Tension (lb.)	1,780	1,840	1,845	1,850	1,850

Span Length.—Although, as will be seen later, the chief factor determining the distance between supports is the contour of the country, other conditions occur to influence the span length. Transmission lines built before the year 1910, when suspension insulators began to come into wide use, were generally limited to 400 feet between towers, or 200 feet between wood poles. With the development of the mechanical side of the art, the benefit derived from longer spans was realized, and

with suspension insulators and 110-kilovolt operation, 600 to 800 feet became usual. In 1922, the 130-kilovolt line of the Victorian Electricity Commission was built from Morwell to Melbourne with spans averaging over 1,000 feet; at the same time the Kings River 110-kilovolt line of the San Joaquin Light and Power Co. was erected in California with 1,200-foot spans, and at the present time at least one high-tension line is being erected in the Southern States with spans which average

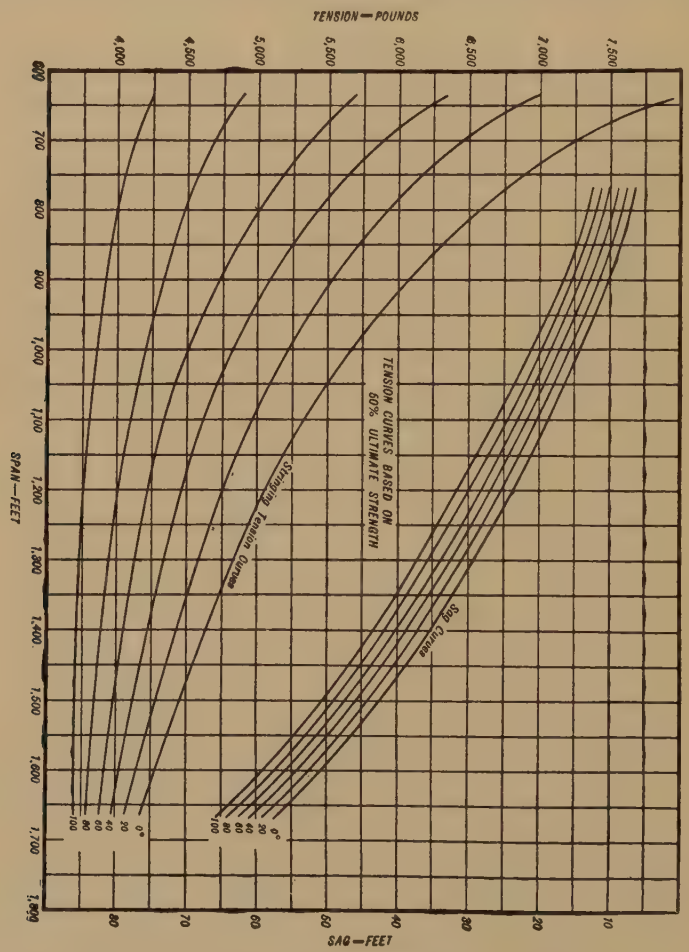


FIG. 80.—Sag and tension values for an aluminum-steel conductor 415,000 cir. mils., with a maximum stress 50 per cent. ultimate strength.

2,000 feet. Turning from averages to maxima, most transmission systems will have a few extra long river or valley crossings, which may be from 2,500 to 5,000 feet in length, and although these are not dictated by economic laws, they have stimulated progress in long span line engineering.

In level country, however, the increase in span length has been due to reasons of reliability and economy. In an electrical sense the transmission line would have maximum reliability if it had no solid support whatever. Air as an insulator is well understood; its breakdown values are known and relatively constant. As soon as a porcelain support is interposed between line and ground a possible cause of failure is introduced. Notwithstanding the remarkably high figure of reliability in modern insulators, the hazard is still present, and when it is considered that a double-circuit line, 200 miles long, with 600-foot spans may have more than 150,000 individual insulator discs, it will be understood how a very small fractional percentage of failures may seriously affect the continuity of service. Extending the span to 1,200 feet will reduce the hazard by one half, at the same time simplifying maintenance and inspection of the reduced number of units.

There is also an economic argument which is generally in favor of the longer span. As the tower spacing is increased, the individual supports become fewer and heavier, because of their greater height, due to increased sag, and their greater weight, due to increased transverse loading. Including in the cost of each tower that of the insulators and hardware, a curve can be plotted showing the cost of material as a function of the span length. Such a curve will fall very rapidly and afterwards rise very gradually, the point of inflection being sometimes termed the " economic span." A good number of other factors must be considered, however, especially construction and right-of-way costs, and since the majority of these items are a function of the number of towers, they will combine to favor a span still longer than that indicated by the cost of material. There is a tendency for " economic span " calculations to point to a span length somewhat shorter than would be derived from

a more complete analysis. Modifications always arise by which the line construction must diverge from the office calculations, and since appreciable variation in the span will usually be necessary in a settled and cultivated country, construction is simplified by adoption of the longest span reasonably practicable. Inspection of stringing curves will show that design is simplified by the adoption of long spans, because the unbalanced tension between two unequal spans is much less if they are long than if they are short.

It is interesting at this time to quote the statement * of E. L. Gemmill, a well-known structural engineer responsible for the design of towers on a number of transmission lines:

> " The trend of American practice to-day in the designing of transmission line installations is to make the spans between supporting structures as great as possible. As the result of considerable study, extending over several years of experience with lines having spans some of which were very short while others were exceptionally long, it has been determined that the best and most economical lines, all things considered, are those in which the supporting structures are spaced far apart.
>
> " This is true even though the first investment for the original installation is somewhat larger in the case of long spans than where short spans are used. It has been determined from comparative records that the maintenance of lines having the long spans is much less than was the maintenance of the same lines during previous periods when shorter spans were used. This decreased cost of maintenance has been proved to be sufficiently important to warrant making larger initial investments on original projects. The maintenance is not only less expensive with the long spans, but it is also less troublesome, because there is less interference with continuous service along the line. This is a matter worthy of careful consideration as the value of electrical service in almost every case is dependent upon the assurance of its continuity.

* " Transmission Towers," Blaw Knox Co., Pittsburgh.

FIG. 81.—ERECTING A HIGH DOUBLE-CIRCUIT TRANSMISSION TOWER ON A 110-KILOVOLT LINE; FOUNDATIONS SET IN THE BED OF THE LAKE (HYDRO-ELECTRIC POWER COMMISSION OF ONTARIO).

[*Facing page 198.*

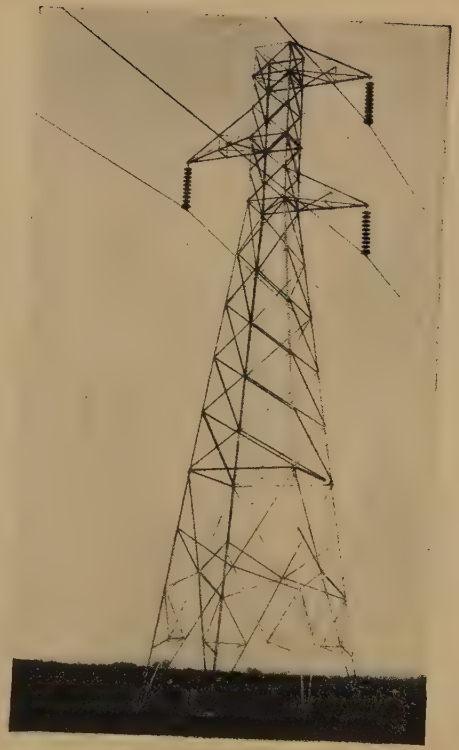


FIG. 82.—SINGLE CIRCUIT TOWER ON A 165-KILOVOLT LINE (PACIFIC COAST STEEL CO.).

FIG. 83.—INSERTING THE "JUMPER" AT AN ANCHOR TOWER.

[*Facing page 199.*

"By using long spans the number of insulators required is reduced; and, as there is always a chance that a flashover will occur at the insulator, it is obviously advisable to reduce the number of insulators to a minimum in order to eliminate, as far as possible, this source of trouble for the service.

"Another advantage derived from the use of long spans is that the variations of stress in the wires resulting from large changes in temperature will be much less than under similar conditions of loading on short spans. The constant changing of stress in the wires is productive of more trouble than higher stresses which are more uniformly applied.

"The long span is especially advantageous for a line carried along a hillside, because it will generally permit of such an arrangement of towers that there will not be any upward pull on any of them. The upward pulls are always a source of trobule, and they should be eliminated wherever conditions will permit an alternative construction. The upward pull causes not only mechanical, but also electrical troubles, because, during a rainstorm, water will run down along the wire into the insulator, which, of course, immediately produces electrical trouble."

For a thorough survey of the possibilities the cost of material and construction ought to be carefully studied, not merely for different tower spacings, but also for different conductor materials, sizes and tensions. In this connection it is possible that some treatises have attached undue weight to the "economic span" theory, assuming these other factors to be constant instead.

Profiles.—Level country is, of course, the exception, and more or less hilly country the rule; consequently, a careful survey must be made of the route of any transmission line and the profile plotted for use in the design office. Such a plan will generally be made with a horizontal scale of between 200 and 500 feet to the inch, and a vertical scale of one tenth as much.

Immediately below the profile is plotted a map of the route showing exactly where the horizontal alignment changes, and this must be read in conjunction with the vertical plan. It is next required to prepare a sag template for the wire to be strung on the line; in other words, a cardboard or celluloid curve which will reproduce to the scale above mentioned the actual catenary of the wire under conditions of maximum sag. In view of the similarity of such curves, it will be seen that the curvature is unaffected by variation in span as long as other conditions remain unchanged; consequently, it is only necessary to make the template cover the maximum span to be strung at standard tension, and all smaller distances can be indicated on it. In making the template, although only the span and maximum sag may be known, the following constants will be useful.

TABLE 45.—*Data for Plotting Catenary Template.*

Per cent. of span.	Per cent. of sag.
10	36
20	64
30	84
40	96
50	100

In using the template for the purpose of "spotting" or determining tower locations, it is expedient to add to the sag a constant vertical ordinate representing the minimum ground clearance. In this way it can be applied directly to the profile and the necessary height and location of the towers defined. The obvious advantage of placing the supports at the highest points will immediately be seen, because longer spans can be used without impairing clearances; in fact, undulating country affords in a considerable degree the opportunity for economical construction. In order to take full advantage of this fact the wire ought to have high tensile properties, and in this respect aluminum-steel is generally superior to copper in having a flatter catenary just as copper is superior to aluminum without reinforcement.

A second template will also be prepared to show the minimum sag, that is, the condition at lowest temperature when the wires

are carrying no ice or wind loading. This will be useful to check the preliminary tower locations for "uplift"; in other words, to ensure that on an incline the conductor support will not be at the lowest point of the wire. Should this condition exist it will be prudent to revise the design so that either the tower is raised, tension reduced, weights added at the lowest point or a dead end introduced. The device of using a tie-down insulator string to hold down the wire at the lowest point is often adopted, but has little to recommend it, and in some instances has been abandoned in favor of weights or other device.

Inspecting the stringing chart it will be noted that at virtually all temperatures the tension in the wires is lower for long than for short spans, although with the addition of ice and wind loads it will, of course, reach the maximum design value for all spans. Another fact already mentioned as arising out of the above is the smaller disparity of tension between two adjacent long spans than between two short ones. This fact simplifies design and construction, because on any line equipped with suspension insulators an unbalanced tension at any support will pull the insulator out at an angle in the direction of the greater load. To a certain degree this is advisable, especially where the insulator string is a long one, but there is a distinct practical limit beyond which it is necessary to use dead-end construction, or some other artifice. If all the spans are of equal length the problems of unbalanced tension do not arise except under conditions of non-uniform ice deposit, but, as already indicated, it is necessary for economic construction to take advantage of the contour of the country so that spans may be both long and variable. To consider a concrete illustration, a high-tension steel tower line on the Pacific Coast was recently constructed having a section with the following spans:

(1) 900 feet (dead-end).	(6) 450 feet (suspension).
(2) 1,000 feet (dead-end).	(7) 500 feet (suspension).
(3) 360 feet (suspension).	(8) 550 feet (dead-end).
(4) 550 feet (suspension).	(9) 700 feet (suspension).
(5) 500 feet (dead-end).	(10) 700 feet (dead-end).

The above represents an extreme instance having a very irregular profile as well as several changes in alignment.

It is in every way unsatisfactory to intersperse dead-end points where they can be avoided, but with considerable variation in the span the alternatives are not numerous, and in the instance cited above unequal spans, together with changes in grade and alignment, call for the unusual proportion of one dead-end tower in every two. On the other hand, so great is the contrary tendency that tower lines with suspension insulators are now built upwards of sixty miles long without a single dead-end point, except at terminals. By this means the ideal mechanical conditions are realized in which loads are carried and distributed through the wires without being transferred to the structures. An unbalanced horizontal tension may be limited by a cast iron weight hung at the bottom of the insulator clamp, and this is in many respects preferable to the use of a strain insulator, as already indicated, because the value of the weight and, at the same time, the strain in the insulator is considerably less than the tension in the wire. It is, moreover, unnecessary to hold the insulator string vertical at all times, but only to limit the deflection to a reasonable angle under the most extreme conditions. The problem of equalizing span tensions is met by considering any portion of the line between two dead ends as a unit independent of every other section. Clearly, when the wire is strung, the tension will be equal throughout the entire section, whatever be the number of spans involved or their respective lengths. But from the stringing curves it is seen that each span length has its appropriate tension at stringing temperature, and the question arises whether to strike an average span throughout the section for calculating the tension or to use some more accurate means. If the spans are long and their mutual disparity is small, the mean span method may be used; if unbalanced tension exists in a greater degree, it may be cared for by weights. In the last resort, where the disparity is considerable, interspersion of dead ends is the only resource.

Instead of calculating the appropriate weight, it is reasonable to argue that, since all estimates of the mechanical character-

istics of the line are based on assumption, it would be more satisfactory to determine the required weights empirically. If the weights are made in circular 50-lb. units which can be assembled on a spindle hung from the insulator clamps, units can be added one by one, and the resulting change in deflection observed. A suitable empirical law can be derived from the number of units found to satisfy the various conditions.

Several laws are available for calculating the " equivalent span." Considering any given section of the line between two dead-end points and containing a series of spans of different length, it is required to ascertain the " equivalent " span. Then, if the constants for this span be adopted in stringing the wire, a condition of equilibrium will be attained. In such a case the equivalent span $L_{eq.}$ is given by

$$L_{eq.} = \sqrt{\frac{\Sigma(L^3)}{\Sigma L}}$$

where L denotes each of the individual spans in the section. Adoption of this value will lead to the minimum unbalanced loads on the insulators.

A method of equalization proposed by Murray F. Idail assumes the appropriate stringing tension for a section of the line to be that applying to the " equivalent span " derived as follows:

$$L_{eq.} = L_{av.} + \tfrac{2}{3}(L_{max.} - L_{av.})$$

The Idail method is very simple, the value of $L_{eq.}$ being determined and read off from the stringing chart together with the corresponding tensions. It is evident, however, that no method of this kind can eliminate insulator deflection between unequal spans at extreme low temperature; it merely affords the best balance possible under the conditions. Application of weights, on the other hand, will definitely reduce the angle of swing, and may become necessary if the unbalanced tension is appreciable.

Reference has already been made to the problem of stringing a line on steep grades with a considerable difference between tower elevations. Besides the possible uplift at the lower point, several other circumstances arise here. In the first place,

the tension in the wire at the upper end is increased by a considerable amount, due to the weight of the wire. In the second place, an additional vertical load is imposed on the upper tower by virtue of the downward component of the wire tension. Since the tower crossarm is designed for horizontal and vertical test loads, it is necessary to resolve the wire tension in two directions. If the conductor direction is downhill at an angle θ with the horizontal, then the horizontal component of tension is

$$T \cos \theta$$

and the vertical component

$$T \sin \theta$$

where T is the maximum tension in the wire. These components should be included in the tower test loads.

Similarly to the changes in grade, the alignment of a transmission line will be subject to many changes, especially in a populous and industrialized country. Every angle in the line adds its quota to the unproductive cost, so it is unnecessary to add that all possible changes in alignment should be smoothed out. The side tension on a support or insulator is

$$2T \sin \frac{\theta}{2}$$

where θ represents the angle by which the alignment changes, and T is the maximum tension in the wires. By rounding off the turn in the line, the side tension can be distributed over three or four towers without calling for dead-end construction, and the reduced load on the insulators will help to increase the mechanical reliability. Side deflection of the insulators must, of course, be allowed for, and this is usually done by designing a special tower for angle positions, giving ample clearance in one direction.

A method for calculating the longitudinal swing of suspension insulators has been devised by Edgar T. Driver.

Let T = tension in conductor at insulator clamp,
H = horizontal component of tension,
W = weight (or loading) per foot of wire,

l = span length in feet,
d = sag in feet,

then, using the parabolic formula,

$$T = \frac{Wl^2}{8d}\sqrt{1 + \frac{16d^2}{l^2}} \qquad (1)$$

also $$H = \frac{Wl^2}{8d} \qquad (2)$$

and $$T = H \sec \theta \text{ or } \sec \theta = \frac{T}{H} \qquad (3)$$

In the above we have

$$\sec \theta = \sqrt{1 + \frac{16d^2}{l^2}} \qquad (4)$$

Since d and l are known, the angle θ can be evaluated. The same operation should be performed for the adjacent span, using appropriate values d_1, l_1, and T_1, derived from the stringing chart. As a result a parallelogram of forces can be drawn the resultant of which is the direction in which the insulator string will hang. If $T_1 = T$, then $\theta_1 = \theta$, and the insulator will be vertical. However, with inequality of tension it will hang at an angle with the vertical. Then

$$\frac{T - T_1}{W} = \tan \phi \qquad (5)$$

and $$M = (T - T_1) \tan \phi \qquad (6)$$

where M is the weight which must be hung on the insulator clamp to keep it perpendicular. The calculations must, of course, be made for the most extreme conditions, *i.e.*, for the lowest temperature; the compensation will then be adequate for all other conditions. It is unnecessary and undesirable to compensate entirely for unbalanced tensions; it should suffice to reduce insulator swing to safe limits.

Spacing and Clearance.—By spacing is meant the interaxial distance between the conductors as arranged on the insulators, whilst clearance connotes the distance from the wires to ground, or other non-insulated object. Both quantities are considered mainly in their electrical relations, but have a distinct mechanical

bearing because the spacing adequate for electrical reasons is sometimes mechanically insufficient. Most tables of spacing values are compiled solely on an electrical basis, and careful study is necessary to determine whether they are sufficient to preclude contact between loaded conductors swung by the wind. Several years ago an extensive mileage of 110-kilovolt line was constructed, using aluminum cables of 212,000 cir. mils and smaller, without reinforcement, strung on 600-foot spans with a spacing of 8 feet, two of the wires in one circuit being in the same horizontal plane. A maximum sag of nearly 30 feet was encountered, and a number of short circuits were experienced. Subsequent construction on the same system abandoned the horizontal arrangement, using the more conventional offset vertical disposition, at the same time increasing the spacing to 10 feet, and using steel-cored conductors, since when none of the earlier troubles have been met. It might be said that the spacing should be some function of the sag of the wires, but a good deal depends upon the wind load experienced and the angle to which the wires may swing. It is generally assumed, and is not contrary to experience, that wires will swing in unison. Irregular conditions will arise, however, to modify this, and it is best to eliminate any horizontal arrangement of wires except where a liberal spacing can be allowed, as when the wires are suspended from the extremities of the crossarms.

A true vertical disposition of the three wires on one circuit is likely to be no less unsatisfactory on account of non-uniform ice loading, and, as treated under the heading of "Towers," a modification of this plan by extending the middle crossarm, or tying in the middle conductor, is very widely adopted. In this way each circuit is disposed in a triangle, but no effort is made to maintain the equilateral plan, which would be far too costly in view of the heavy crossarms and tower bracings called for. With the offset vertical plan the following spacings will be found normal for copper or aluminum-steel conductors strung on spans of 600 to 800 feet. For almost any case these figures should be subject to study, and possibly to revision.

Some appreciation of the diversity of practice in spacing can be realized by reference to the diagram (Fig. 84). Without doubt, however, the practice is narrowing down and becoming more uniform.

TABLE 46.—*Spacing Between High-tension Conductors.*

Kilovolts.	Spacing in feet. (Pin-type insulator.)	(Suspension insulator.)
11	2	—
22	3	—
44	4	—
66	5	6
88	—	8
110	—	10
132	—	12
154	—	14
220	—	18

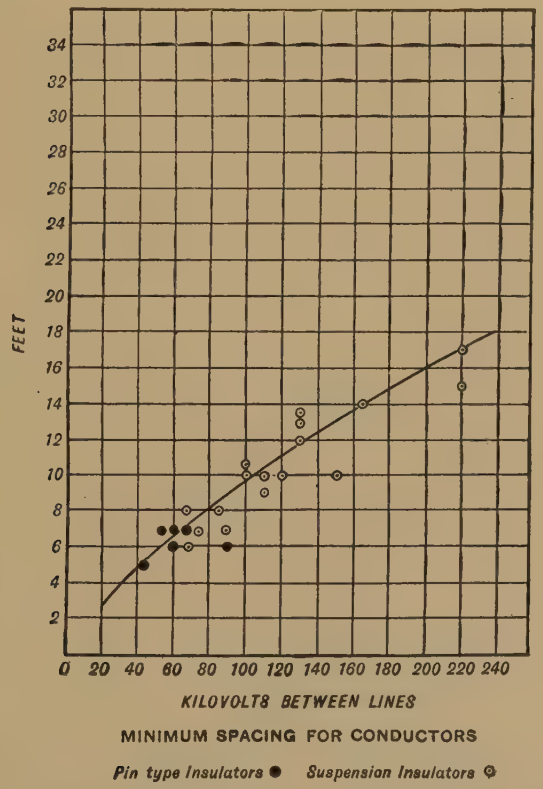


FIG. 84.—Empirical curve for spacing of high-tension conductors.

Clearance to the nearest part of the tower or other grounded structure is usually based upon the maximum transverse insulator deflection. In most cases this is assumed to be 45 degrees, but in some instances it was considered necessary to estimate a swing of 60 degrees from the vertical. This would not only bring the conductor wire correspondingly near the tower frame, but any swing of more than 45 degrees would also begin to approach the crossarm above, so that it is necessary to design with a " drooped " or " umbrella " type of arm, or alternatively to suspend the top insulator unit from a link or bracket. Considering a 150-kilovolt insulator string of ten units 5 feet long, deflected at 45 degrees from the vertical, the minimum clearance allowable from the wire clamp to the tower basket would be 4 feet, and the horizontal displacement of the conductor with the above deflection would be

$$l \sin \theta$$

where l is the length of the insulator string. This displacement is 3½ feet, to which is added 4 feet clearance, and probably 2½ feet for half the width of the tower column or " basket," giving a total length of arm measured from the tower axis of 10 feet. The offset arm ought to be about 2 feet longer. Estimate of clearances is best made graphically, as it may be found that the tie rod of a lower crossarm impairs clearance, in which case the design must be modified.

The actual values of minimum clearance to the tower frame under the conditions outlined will vary from 3 to 6 feet for an operating voltage of 110 to 220 kilovolts (*i.e.*, 63.6 to 127 kilovolts to ground with the usual grounded **Y** connection), and are based upon the spark over voltage with a reasonable safety factor.

Ground clearance is generally from 20 to 30 feet, and is usually based on extreme possibilities, such as a loaded hay wagon being driven under the line, and with a laborer standing on top of the load with a pitchfork. Some such empirical reasoning as this must be followed, except where specific rules are laid down. In the code of the British Electricity Commission-

ers, ground clearances at a temperature of 122° F. are clearly specified as follows:

TABLE 47.—*Ground Clearance for High-tension Wires.* (*British Rules.*)

Kilovolts (max.).	Clearance (feet).
66	20
110	21
165	22
Over 165	23

For railway crossings the requirements are somewhat more strict, and for highways, telephone lines and other forms of communication special conditions must be fulfilled. The National Electric Safety Code, already cited as the standard of good practice in the United States, specifies a minimum vertical clearance of 30 feet from the rail to the wire, with additions for more than 50 kilovolts. For ordinary clearances, the code differentiates between highways over which a vehicle may pass and those traversed only by pedestrians.

TABLE 48.—*Ground Clearance for High-tension Wires.* (*National Safety Code.*)

	Crossings over			
	Highways.		Footpaths.	
Kilovolts (max.).	ft.	ins.	ft.	ins.
66	20	8	17	8
110	22	6	19	6
165	24	10	21	10
220	27	1	24	1

Long Crossing Spans.—The occurrence of a long valley, ravine, or river in the profile may necessitate special construction diverging from the economic scheme. Such crossings have been built up to a length of over one mile between supporting structures, and, in a number of transmission schemes now being planned, longer spans than this are under consideration, and would seem to be economically practicable. For a given length of span, the factors of the problem may vary between wide limits. A deep ravine or gorge is relatively the most simple crossing to design, because the sag need not be strictly limited, the wires following the contour of the gorge. By this means the tension will be reduced, and the load on the insulators and structures will not be as great. At the same time, it is probable

that standard conductors can be used. With such a span, however, care must be taken to secure sufficient spacing because deep ravines are often visited with gusts of wind travelling in an upward direction, and there is a possibility of short circuit from this cause. Adjacent conductors should, if possible, be spaced neither in the same horizontal nor vertical plane. Long spans across a navigable river or harbor are complicated with other considerations than the above. In the first place, the banks are often flat, giving no elevation for the tower bases; in the second place, a clearance of from 150 to 250 feet may have to be provided above high tide level. These conditions lead to a tower height of 300 to 400 feet for a crossing of the order of 4,000 feet long. In such a case one of three alternative designs may be followed, either (*a*) the wires may be anchored direct to the main towers, which must therefore be designed for the maximum tension of the wires, besides which the duty on the insulators is extremely severe; or (*b*) the conductors are carried over insulated sheaves on the main towers and anchored to short, heavy structures located a few hundred feet back; or (*c*) the wires are carried over sheaves as above and connected to balance weights operating in vertical runways to maintain a constant tension in the conductor.

One of the most important problems to be solved in the design of long crossings is that of periodic vibration of the conductor wires. In order to secure the requisite clearance it is usually necessary to string the conductor very tightly between its supports and for this reason some form of high tensile material, either steel, bronze or a composite cable, is generally used. Such a wire will however partake of the nature of a bowstring and will be subject to a periodic oscillation relatively small in magnitude but leading to a continual bending of the wire where it is gripped by the clamps. Such an action is apparently not dependent on strong winds, in fact these appear to damp the vibrations, but is evidently caused by almost imperceptible air currents in what might be termed calm weather. According to observations reported by engineers of the Southern California

Edison Company these oscillations may have a frequency of 15 to 30 cycles per second and an amplitude of one inch. The distance between nodes was twelve to sixteen feet. It is clear that the vibration in itself puts little or no stress on the wire; the difficulty is met where the conductor is gripped in a heavy

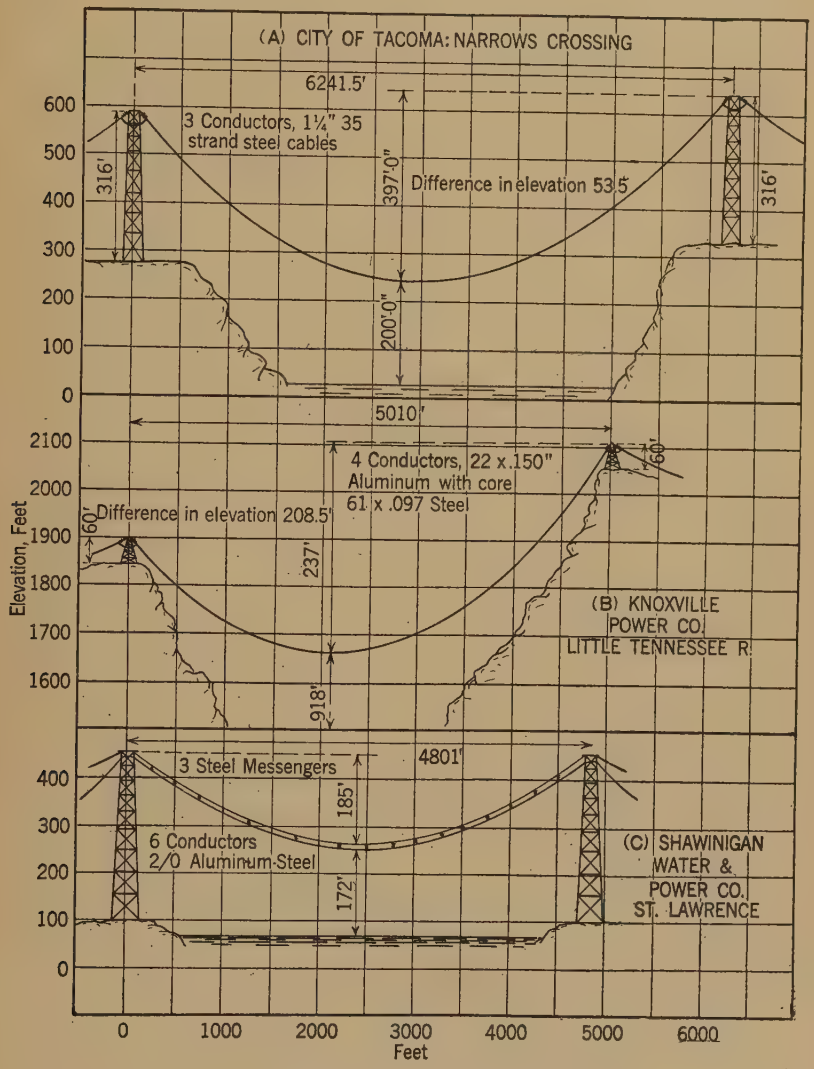


FIG. 85.—Long crossing spans. (See Table 49.)

clamp at the end of the span. Here the oscillations are checked with the result that wires in the envelope of the cable have been found to break off one by one. Various devices have been employed to mitigate the trouble; springs and weights have been introduced, clamps have been reduced in weight and short lengths of cable of the same character as the main con-

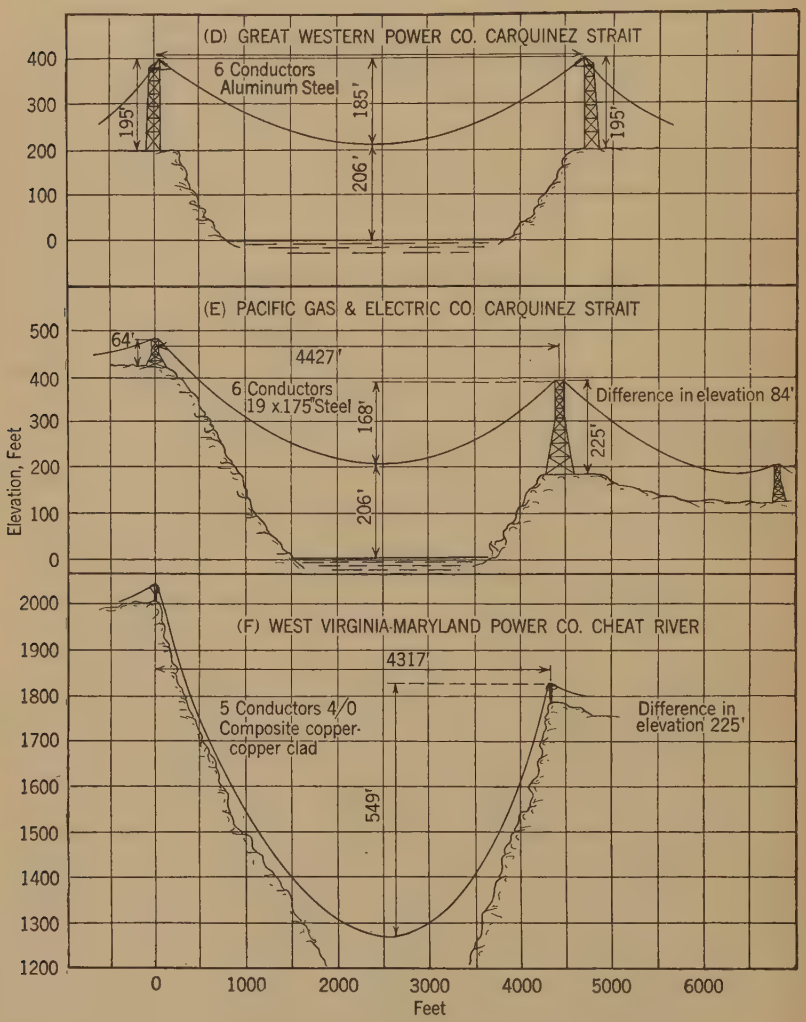


FIG. 86.—Long transmission spans. (See Table 49.)

ductor have been clamped to it for a fixed distance from each of the supports. The following summary of practice in construction of a number of exceptionally long crossings will indicate what devices have been adopted in each case.

As far as is known at present the longest transmission line span yet constructed is that of the City of Tacoma which crosses a distance slightly over 6,241 feet over the Narrows of Puget Sound. The line operates at 100 kilovolts and consists of two circuits of special 35-strand steel cable (see Fig. 15). This cable is 1.25 inch diameter, 1,180,000 cir. mils in size and has a tensile strength of about 210,000 lb. per square inch or 180,000 lb. for the entire cable. A maximum working tension of 60,000 lb. is adopted, this allowing for ice loading of one half inch and wind loading of 8 lb. per square foot at a temperature of zero Fahr. The main towers are each 316 feet high, but the difference in elevation of the banks and of the conductor supports is 53½ feet. At these main towers the wire is held by a clamp and strain insulator and next passes over a sheave six feet in diameter, being anchored in concrete a distance respectively 900 and 926 feet back of the east and west towers. Each main cable is anchored into a socket bridge piece held by the insulator yoke. Two relieving cables are served around and clamped to the main cable respectively 70 feet and 90 feet out from the insulator yoke. They are attached to the bridge socket by tension adjusters, so that a positive load can be put upon these cables and thereby the load on the main cable relieved at the point of attachment as well as reducing the effect of vibration. Insulation of the crossing is taken care of by a yoke of twelve strings, each string of eleven high strength strain insulator units; the entire crossing with its six conductors therefore necessitates the use of 1,584 insulator discs. This large number is coupled with a very conservative safety factor both in the mechanical and the electrical sense.

Two problems have been faced in this particular installation: the damping of destructive vibration in the main conductor by the attachment of auxiliary cables in the vicinity of the dead-

end clamp and the allowance for horizontal travel of the main cable by the use of a sheave. This latter as already mentioned is six feet in diameter and operates on a seven-inch shaft mounted in bronze bearings. According to calculations made by the designers a movement of fourteen inches is to be expected, this being due to the unequal expansion of the wire on the long span and the adjacent short span.

The next longest span of record appears to be that of the Knoxville Power Company in Tennessee, where a 150-kilovolt line is carried across the Little Tennessee River a distance between supports of 5,010 feet. In general this is a much less difficult problem than the span just described because the great depth of the valley permits stringing with relatively lower tension and higher sag. The conductors are of the aluminum-steel type having a steel core of 61 wires .097 inch and an aluminum envelope of 22 wires .150 inch. Ultimate strength of the complete cable is 82,000 lb. and the maximum operating tension is 30,000 lb. The upper conductor of the group is strung somewhat more tightly, so that a local or temporary loading on this wire is less likely to lead to a short circuit. There are three main conductors on this crossing as well as a fourth which is separately insulated and provided with disconnecting switches to act as a reserve. A difference in elevation exists between the two supports amounting to 208 feet, but it has not been thought necessary to compensate for this and both towers are of the same height of 60 feet and weigh 55,000 and 57,000 lb. respectively. Oscillations and vibrations of the wires have not been reported. It will be noted that these towers act as anchor points, the wires being attached to the crossarms by strain insulators, and the structures therefore are designed to withstand the entire sum of the horizontal forces in the wires. In the Narrows crossing previously described the main cables are carried over the sheaves on the crossing towers and the horizontal component of the wire tension is transferred to the concrete anchors several hundred feet back. This arrangement is usually more economical where the crossing towers are very

high because of the great weight of steel which would be called for if the entire horizontal load were imposed at the top of the structure. In the Knoxville Power Co.'s span the height of structure is relatively low and towers of reasonable weight can therefore be designed to carry the load. Insulation of this crossing as originally designed incorporated a strain type of unit in which the tension member consisted of two straight hickory sticks mounted between suitable end clamps and immersed in oil in a porcelain sleeve. This device has since been abandoned in favor of a multiple yoke assembly of standard porcelain insulator units. At the dead end the aluminum envelope is tapped off to form the usual jumper, and the steel core, which carries virtually all the tension, is anchored into the customary bridge socket, which is in turn connected to the clevis on the insulator yoke by means of a spiral steel spring.

Another long span of considerable importance and involving some novel features of design is that of the Shawinigan Water and Power Company across the St. Lawrence River near Three Rivers, Quebec. This waterway forms one of the main routes of commerce and clearance must therefore be allowed for ocean steamships. Length of the crossing between supports is 4,801 feet and this is spanned by three stranded steel messenger cables which are carried over the towers and anchored in concrete respectively 951 and 571 feet back on either side of the crossing. The steel cables are rope stranded to combine strength with flexibility and have each a section of approximately .980 square inch. Tensile strength of the cable is 227,000 lb. per square inch, giving an ultimate tension of 222,000 lb. for the cable. The maximum operating tension with full winter loading is 106,000 lb. Horizontal displacement of the main cables is allowed for by the provision of steel sheaves eight feet in diameter. The actual conductors are of stranded aluminum suspended from the steel messenger cables by means of standard suspension insulators spaced 250 feet apart. Each steel cable supports two conductors separated by a crossarm and separately insulated. Such an arrangement as this possesses the great

merit that the mechanical tension on the main crossing cables does not have to be carried by any insulator, in other words these cables are at ground potential. There are also no special arrangements required in respect of clamps or tappings. Vibration may be experienced due to the high mechanical tension and the great length of the span; its effects however will be confined to the steel wire and clamps, which will probably be fully resistant to the loads imposed. In no event can the conductor wires or the insulators feel the effect of any vibration or oscillation.

Up to the present this appears to be the only important installation of a long transmission crossing using a messenger cable and suspending the conductors. As already indicated there are distinct merits in the arrangement especially as it does not require the full tension of the crossing to be carried by the insulation. On the other hand the suspension insulator units are very inaccessible and their condition can be ascertained only by shutting down the line and inspecting from a trolley.

Two important transmission systems span the Straits of Carquinez in California, the Great Western Power Co. and the Pacific Gas and Electric Co. The longer of the two spans is the first named, being 4,753 feet between towers. The Straits, which form the combined estuary of the Sacramento and San Joaquin Rivers, are of course navigated by ocean vessels and a minimum clearance of 206 feet is required above high water. Six conductors of aluminum-steel are carried across the Straits, being anchored through strain insulators to the main towers, which are 195 feet high. Each conductor consists of a thirty-seven-strand steel core surrounded by twenty-four strands of aluminum, all being of .095 inch diameter. The insulator assembly for each conductor consists of a yoke of eight strings each of fifteen units; a total of 1,440 individual units is therefore associated with the complete installation. Equalization is obtained by attachment of the yoke to the insulators through the medium of steel spiral springs, of which there is one to each insulator string. The maximum tension on any one conductor

FIG. 87.—A LONG CROSSING SPAN AT BEAVER HOLE, WEST VIRGINIA, SUPPORTED BY STEEL CHANNEL POSTS AND TRIPLE YOKE J.D. INSULATORS.

[*Facing page 216.*

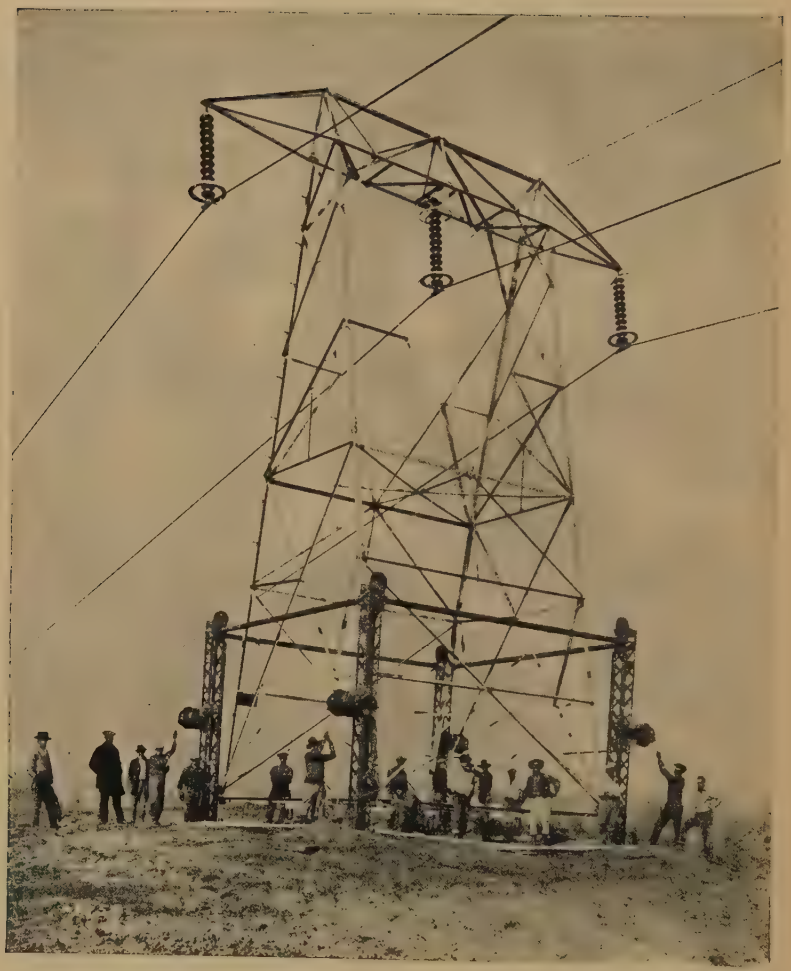


FIG. 88.—HOISTING A TOWER FOR THE INSERTION OF EXTENSION MEMBERS TO GIVE INCREASED CLEARANCE. LINES IN SERVICE AT 150 KILOVOLTS.

[*Facing page 217.*

or insulator assembly is 20,000 lb., considered as a dead end, therefore each structure must support an unbalanced horizontal load, due to six wires, of 120,000 lb., in addition to transverse wind and vertical weight loads. A certain amount of troublesome vibration has been experienced in the wires on this crossing, but in general it has operated with entire reliability.

Where the Pacific Gas and Electric Co.'s lines cross the Straits the actual length between supports is 4,427 feet and this span was put across in the year 1901. This installation was operated at 66 kilovolts and with the increase to 110 kilovolts in the year 1922 some important modifications were made in the construction. Referring first to the conductors, these are of nineteen-strand steel cable laid up with individual wires of .175 inch diameter. On the high or south side of the crossing is one of the main towers, 64 feet high, the wires are anchored 140 feet back and carried over the south tower by means of a saddle mounted on rollers and supported on a pedestal insulator assembly. On the north side of the crossing the main tower is 225 feet in height to compensate partially for the low elevation of the ground. Here the wires pass over a similar saddle and insulator assembly, but owing to the nature of the ground the anchors are set much farther back than on the south side. A supporting tower is provided 1,385 feet back of the north tower and thence the wires are brought down to the anchorage 325 feet beyond. At the anchorage each steel cable is carried around a sheave 24 inch diameter and snubbed off. The axis of each sheave is anchored to a structural steel equalizing framework supported by pedestal insulators. It is noteworthy that throughout the entire installation all insulator porcelain is in compression. In the manner previously described, reinforcing cables are clamped to the main cables for a distance out from each of the supporting saddles and are provided with turnbuckles so that they can relieve the main conductors of considerable stress. This device is believed to damp vibrations and prevent failure of the wires at the clamp.

Construction of an unusual type is employed in a long span

of the West Virginia-Maryland Power Co. crossing the Cheat River in Maryland. The distance between supports is 4,317 feet, with a difference in elevation of 225 feet; since, however, the crossing is over a deep and undeveloped valley the clearance limits are liberal and it has been possible to string with a maximum sag of 549 feet. The conductors are five in number, each having a core of seven strands copper-clad steel with an envelope of twelve strands copper, all wires being .106 inch in size. Each wire is dead ended through an equalizing sheave and a triple yoke of six insulator units to a vertical twelve-inch steel I section set in concrete. It is obvious that wide horizontal spacing of the conductors is necessitated by the very considerable sag allowed; this would lead to a very heavy and costly structure if a conventional tower were used. With the present arrangement of a single post for each conductor a liberal spacing can be employed.

The main proportions of the foregoing six long spans are shown in Figs. 85 and 86 and particulars are set out in Table 49. It will be seen that the methods of construction are quite diverse even where conditions are similar; experience now being derived will however probably lead to more standardized construction in future installations. In many instances the relative merits of overhead and submarine crossings are compared before the final design is made. In such a case it is interesting to note the sentiment of the engineers of the Shawinigan Water and Power Co. This utility not only operates the 4,800-foot span across the St. Lawrence River but a crossing of submarine power cables also. The decision to build the overhead span was based not on economy of first cost, because submarine cables could have been laid fifty thousand dollars cheaper, but because it showed superior reliability

In designing long spans it will be found that steel-cored conductors and structural steel towers are entirely adequate for all ordinary conditions. The insulator problem, however, is not yet satisfactorily solved, and although the loads are as far as possible converted into compression, they are not static; longi-

TABLE 49.—*Data on Long Crossing Spans.* (*See Figs. 85–86.*)

System.	Location.	Distance between supports.	Conductors.			Number.	Tension. Max.	Sag. Max.	Clearance. Min.	Notes.
			Material.	Area. Sq. in.	Stranding.					
City of Tacoma.	The Narrows, Washington.	6,241 ft.	Steel.	0.93	35×0.177,195	6	60,000 lb.	397 ft.	200 ft.	Difference in elevation 53½ ft., height of towers 313 ft., weight each 260,000 lb., cables anchored 900 ft. back of towers.
Knoxville Power Co., Tennessee.	Little Tennessee River.	5,010 ft.	Aluminum-steel.	Al. 0.390 St. 0.450	Al. 22×0.150 St. 61×0.097	4	30,000 lb.	237 ft. (80° F.)	500 ft.	Anchored on main tower with a 208 ft. difference in elevation. 8-yoke insulator. Weight tower: (*a*) 55,000 lb. (*b*) 57,000 lb.
Shawinigan Water and Power Co.	St. Lawrence River.	4,801 ft.	Steel carrier. Aluminum-steel conductor.	0.980 Al. 0.132	—	3 6	106,000 lb. 12,000 lb.	228 ft.	150 ft.	Steel cables anchored on concrete blocks respectively 951 and 571 ft. in rear of high towers. Conductors suspended from steel cables.
Great Western Power Co.	Carquinez Strait, Cal.	4,753 ft.	Aluminum-steel.	Al. 0.171 St. 0.262	Al. 24×0.095 St. 37×0.095	6	20,000 lb.	—	206 ft.	Wires anchored on main towers. 8-yoke insulator.
Pacific Gas and Electric Co.	Carquinez Strait.	4,427 ft.	Steel.	0.460	19×0.175	6	21,100 lb.	147 ft.	206 ft.	Wires anchored 1,710 ft. and 140 ft. behind main towers and carried over roller saddles with spring equalizers. Tension at 75° F.
West Penn Power Co.	Beaver Hole, W. Va.	4,317 ft.	Copper-clad core copper.	0.166	Cu. 12×0.106 C.C. 7×0.106	5	7,500 lb.	549 ft. (normal).	—	Each wire is anchored to a post, consisting of a 12 in. I beam set vertically in concrete foundation.
Union Elec. Light & Power Co.	Mississippi River, Mo.	4,279 ft.	Aluminum-steel.	Al. 0.25 St.	Al. 24×0.115 St. 43 various	6	33,500 lb.	318.3 ft.	74 ft.	Difference in elevation 185.5 ft. Cables anchored on high tower and 2,081 feet back of low tower.
Mississippi River Power Co.	Missouri River.	3,182 ft.	Copper-steel.	Cu. 0.164	Cu. 20×0.102	6	24,000 lb.	160 ft.	70 ft.	Wires anchored at main towers with 6-yoke insulator.
Canadian Niagara Power Co.	Niagara River.	2,192 ft.	Copper-clad steel.	0.155	19×0.102	6	5,400 lb.	65 ft.	130 ft.	Wires anchored at south shore, thence carried over saddle on south tower across river to sheave and jockey weight at north tower.

tudinal movement and oscillations must involve dynamic loads on the porcelain which are difficult to withstand. Up to 110 kilovolts the difficulty is not as great, because pedestal type insulators are practicable. For higher voltages suspension units become necessary, being held in tension and subject to vibration. The tendency is to deteriorate under these severe conditions.

Changes in Design.—One of the most interesting problems arises when a transmission line has to be modified to meet new conditions. The tendency with the growth of power systems is for them to consolidate, both financially and physically, and it is the business of the engineers to eliminate all material differences which would hinder the transmission system from operating as a single unit. In some instances it has been necessary to consolidate a network operating at 60 kilovolts with one at 110 kilovolts. This generally involves a change from pin-type to suspension insulators, although, in one or two cases by using an extra large unit, 110 kilovolts has been impressed upon the former type. Nevertheless, special insulators have had to be installed. The 60-kilovolt single-circuit tower line of the Niagara Lockport and Ontario Power Co. was changed to a 110-kilovolt double-circuit line by removing the pin insulators and supports, adding a small extension to the apex of the tower, and mounting three steel crossarms from which the suspension units were hung. The original structures (except for reinforcement at dead ends) remaining after fourteen years' service at the lower voltage have ample strength for the new conditions. In such a re-designing the principal problem is to maintain sufficient spacing and clearance; it will generally be found that towers designed for the stresses of a pin-type insulated line will have sufficient reserve strength for the more flexible conditions of suspension insulator construction except where the conductors are dead ended. At the present time, even for relatively low-operating voltage, the tendency is to design for suspension insulators and with ample spacing in view of possible increase in pressure at a later time.

During the years 1922–1923 the 150-kilovolt tower lines of

the Southern California Edison Co. were re-designed for operating at 220 kilovolts. Originally the wires were spaced 17 feet 6 inches apart in a horizontal plane, which gave sufficient clearance and spacing for the higher voltage. However, the vertical distance to ground, originally 25 feet from the lowest point of the wire, had to be increased to 30 feet as well as compensating for an extra foot due to two additional insulator units added to each string. The most economical plan was found to be the raising of the towers throughout the line by inserting a four-post rectangular extension immediately above the ground stubs, hoisting the tower to the requisite height before bolting the extension into place. Whilst this was essentially more of a construction problem than one of design, it illustrates an eventuality which may be prepared for by careful work in the design office.

Re-design is sometimes called for by reason of unforeseen severity of loadings and climatic conditions. In some instances heavy sleet loading the first winter a line was in service has pulled the wire through the clamps, broken strain insulators, and involved other troubles; re-design has usually been directed to achievement of greater flexibility by eliminating strain points where possible, substituting weighted insulators hung vertically, addition of links to the insulators and, possibly, reduction in the wire tension. An interesting example of a line being re-designed and re-constructed occurred on a 110-kilovolt network in Canada, where, with a view to improving the mechanical characteristics aluminum-steel conductors were substituted for aluminum. The original cables were removed, reeled and shipped to the cable factory, where the wire was unreeled, unstranded, straightened, and stranded up over a steel core. A change in conductor wires is a contingency which has often arisen. Under the abnormal economic conditions of the war a number of power companies found it possible to remove many miles of aluminum wire from their system to sell it in the open market and replace with copper wire after netting a very substantial profit. In such an event a new series of constants must be

adopted in the design office, new tables worked out for sag and tension, and the line rebuilt on the revised basis.

Routine Design.—The fundamental factors in high-tension line design are of an electrical character, and are primarily concerned with the derivation of the appropriate size of wire, interaxial spacing and arrangement with regard to the electrical load which the line must carry and to the operating characteristics. Electrical reasons also dictate the number of insulator units and the lengths of string. From this point the mechanical design begins, and the business of the engineer is to achieve the most economical result which will meet the electrical requirements, as well as sustain the external loads. Whilst the size of conductor may be assumed as constant, a complete economic study would comprise the following variables:

(*a*) *Material of Conductor.*—Generally limited to copper, aluminum-steel, and aluminum, or, for special conditions, possibly copper with a bronze or copper-clad core.

(*b*) *Tension in Conductor.*—Probably 50 per cent., 40 per cent., and 30 per cent. of the ultimate strength, considered as alternatives and related to the maximum loading.

(*c*) *Average Span Length.*—Values of 400 to 2,000 feet may be studied, depending on the size of conductor and, more important still, on the profile.

For a study to be reasonably complete, all the above variable factors should be surveyed according as conditions permit. Conductors, as already seen in the first chapter, may reasonably be either of copper, aluminum-steel, or aluminum, according to the prevailing market price of the different metals. Certain contingent economy is generally derived from the use of the higher-strength wire, so that even a slightly higher cost of the conductors may be justified. Electrical conditions must also be considered. At voltages of 150 to 250 kilovolts it is seldom that the ohmic resistance of the wire is of primary significance; usually the diameter and make-up of the cable are more important than its area. For this reason, it is not neces-

sary for an aluminum conductor to have the same conductance as the copper which it replaces. This would demand a steel-cored aluminum cable of 60 per cent. greater conductive area than the copper; in actual practice it is more usual to employ aluminum of from 15 to 30 per cent. increased area. Other electrical phenomena, such as corona, charging current, and reactance, being considered, combine to minimize the old-established basis of comparison of a given ohmic resistance. This fact will considerably modify the cost of wire, the mechanical loading, cost of towers, and span lengths.

The most suitable tension must be considered in connection with the appropriate conductor. Whilst it is true that official rules in most countries permit the maximum stress in the wires to be 50 per cent. of the ultimate value, it is not necessarily economical to design on this basis, especially where large conductors of high tensile strength are used. If the contour and angles in the line require many dead ends, the operating characteristics as well as the construction economy may be improved by reducing the stress to 40 or even 30 per cent. of the ultimate strength of the wires, at any rate, for certain sections of the line. Sags and tower heights will be greater; and the spans may have to be modified, but this will be compensated by the reduced test loads and weight of the towers. The only successful method of determining the satisfactory tension is to calculate out two or three different values and apply the respective templates to the profile in the customary way for tower locations. In every event the profile must of necessity be referred to, as only in unusual cases is it possible to figure upon a " standard span " or a long stretch of flat country devoid of physical interruptions or changes in contour.

This selective process of transmission line design by elimination of the least satisfactory schemes one by one is extremely laborious, but no method has yet been found of reducing it to a matter of simple formulæ. Certain theses have been published based upon the assumption that the weight of steel in a tower is proportional to the test loads, and to some power of

the height, but in the field of practical design all these theories fall by the wayside. The method of calculating out a series of hypothetical installations, gradually narrowing them down to the most promising and checking the results by reference to empirical data, may not be scientific, but at the present stage of the art is the best means available.

In the following table an example is shown of a summarized calculation for determining the outline mechanical characteristics of a transmission line. It is specified that the alternative conductors shall be copper of 255,000 c.m. (0.20 square inch) section, and aluminum-steel of the same ohmic resistance of 415,000 c.m. (0.327 square inch) conductive area. Double-circuit construction is to be used, the line transmitting 100,000 kva. at 150 kilovolts over a distance of 100 miles.

TABLE 50.—*Preliminary Mechanical Design for a Double-Circuit 150-kilovolt Transmission Line.*

	Copper.	Aluminum-Steel.
(A) CONDUCTORS.		
Area (sq. in.)	0.200	0.327
Area (cir. mils)	255,000	415,000
Ohms per mile	0.0408	0.0408
Stranding	7 or 37	30 + 7
Diameter of strands (in.)	0.193 or 0.083	0.118
Diameter of cable (in.)	0.581	0.826
Weight per 1,000 ft. (lb.)	780	656
(B) LOADING.		
Ice thickness, radial (in.)	½	½
Loaded diameter (in.)	1.581	1.826
Weight per foot (lb.)	0.665	0.836
Weight conductor per foot (w) (lb.)	0.780	0.656
Total weight (W) (lb.)	1.445	1.492
Wind pressure per square foot (lb.)	8	8
Wind load on conductor (P) (lb.)	1.05	1.22
Resultant load conductor (R)	1.79	1.93
Ratio $R/w(\sigma)$	2.30	2.94
(C) PHYSICAL PROPERTIES.		
Ultimate strength of wire (lb. sq. in.)	54,000	52,000
Maximum stress (40 per cent.) (lb. sq. in.)	21,600	20,800
Gross area (sq. in.)	0.200	0.403
Maximum tension (lb.)	4,320	8,400
Yield point of wire (lb. sq. in.)	30,000	A. 13,000 S. 130,000
Elongation of wire (per cent.)	1	A. 1.9 S. 4.0

TABLE 50.—*Continued.*

	Copper.	Aluminum-Steel.
(D) CATENARY CONSTANTS.		
Modulus of elasticity (lb. sq. in.)	18×10^6	13×10^6
Specific extension (λ)	0.00120	0.00159
Expansion coefficient (α)	9.6×10^{-6}	10.5×10^{-6}
Unit tension for 400 ft. span	6.10	—
" " " 600 " "	4.05	7.3
" " " 800 " "	3.02	5.4
" " " 1,000 " "	2.42	4.3
" " " 1,200 " "	2.02	3.6
" " " 1,400 " "	—	3.1

(E) SAGS AND TENSIONS.

Copper Conductor.

SPAN.	400 FEET.		600 FEET.		800 FEET.		1,000 FEET.		1,200 FEET.	
Temp. °F.	Sag. Ft.	Tension. Lb.	Sag. Ft.	Tension. Lb.	Sag. Ft.	Tension. Lb.	Sag. Ft.	Tension. Lb.	Sag. Ft.	Tension. Lb.
0	6.0	2,640	16.2	2,200	31.6	2,030	51	1,950	75	1,930
20	6.6	2,340	16.8	2,080	32.3	1,990	51.6	1,930	75.6	1,914
40	7.15	2,200	17.4	2,020	33.0	1,954	52.2	1,910	76.2	1,898
60	7.70	2,040	18.0	1,960	33.7	1,917	52.8	1,890	76.8	1,882
80	8.20	1,910	18.7	1,880	34.3	1,880	53.4	1,870	77.4	1,866
100	8.80	1,780	19.5	1,840	35.0	1,845	54	1,850	78	1,850

Aluminum-Steel Conductor.

SPAN.	600 FEET.		800 FEET.		1,000 FEET.		1,200 FEET.		1,400 FEET.	
Temp. °F.	Sag. Ft.	Tension. Lb.	Sag. Ft.	Tension. Lb.	Sag. Ft.	Tension. Lb.	Sag. Ft.	Tension. Lb.	Sag. Ft.	Tension. Lb.
0	—	—	12.8	4,120	22	3,600	36	3,280	52	3,180
20	—	—	14.0	3,760	23	3,400	37.2	3,180	53.2	3,100
40	—	—	15.2	3,440	24	3,200	38.4	3,080	54.4	3,020
60	—	—	16.5	3,180	25	3,060	39.6	2,960	55.6	2,950
80	—	—	17.5	2,970	26	2,920	40.8	2,900	56.8	2,880
100	—	—	18.6	2,790	27	2,790	42	2,800	58	2,810

(F) TOWER DIMENSIONS.

	Copper.			Aluminum-Steel.		
1. Type of tower	Suspension.	Semi-anchor.	Anchor.	Suspension.	Semi-anchor.	Anchor.
2. Ground clearance (ft.)	25	25	25	25	25	25
3. Maximum sag (ft.)	25	25	25	25	25	25
4. Vertical spacing (ft.)	12	12	12	12	12	12
5. Insulator (horizontal projection) (ft.)	5	3	1	5	3	1
6. Top crossarm to apex (ft.)	6	6	6	6	6	6
7. Total: Ground to apex (ft.)	85	83	81	85	83	81
8. Width of base (ft.)	25	25	25	25	25	25

NOTE. The most appropriate span length derived as a basis for estimating is 750 ft. for copper and 1,000 ft. for aluminum-steel wires. These values are subject to revision as well as to the profile of the route.

(G) TEST LOADS.

	Copper.			Aluminum-Steel.		
1. Type of tower	Suspension.	Semi-anchor.	Anchor.	Suspension.	Semi-anchor.	Anchor.
2. Number of broken wires	1	3	6	1	3	6
3. Tension per wire (lb.)	4,950	4,950	4,950	9,900	9,900	9,900
4. TOTAL LONGITUDINAL LOAD (lb.)	4,950	14,850	29,700	9,900	29,700	59,400
5. Length of span	750	750	750	1,000	1,000	1,000
6. Wind load per ft. (lb.)	1.05	1.05	1.05	1.22	1.22	1.22
7. Total wind on wires (lb.)	4,740	4,740	4,740	7,320	7,320	7,320
8. Wind load on structure (lb.)	1,200	1,200	1,200	1,400	1,400	1,400

(G) TEST LOADS—*continued.*

	Copper.			Aluminum-Steel.		
Type of tower	Suspension.	Semi-anchor.	Anchor.	Suspension.	Semi-anchor.	Anchor.
9. Side tension of 5 degrees angle (lb.)	2,450	2,450	2,450	4,980	4,980	4,980
10. TOTAL TRANSVERSE LOAD	8,390	8,390	8,390	13,700	13,700	13,700
11. Weight of wires and ice	6,500	6,500	6,500	8,950	8,950	8,950
12. Weight of insulators	600	1,200	2,400	600	1,200	2,400
13. Tension of 5 degrees vertical angle	2,450	2,450	2,450	4,980	4,980	4,980
14. TOTAL VERTICAL LOAD	9,550	9,550	9,550	14,430	14,430	14,430

NOTE.—The longitudinal test load (G4) is divided and applied at one, three or six crossarm extremities according to the type of tower. Transverse load (G10) is applied at three and the vertical load (G14) at six crossarm extremities. All loads are applied simultaneously.

In reviewing the tabulated quantities it will be seen that conservative and heavy construction has been employed. Maximum tension in the conductors under the worst conditions of wind and ice amounts to 40 per cent. of the ultimate strength, or a factor of safety of 2½. Test loads on the towers correspond to one, three, and six broken wires for the suspension, semi-anchor, and anchor structures respectively. Every tower will sustain the wires on the appropriate span against the side tension of an angle of 5 degrees in addition to the maximum wind loads; for sharper turns on a standard tower, it will be necessary to shorten the span more or less. The same tower will, at the same time, support the vertical load corresponding to a declination of 5 degrees in grade, a very significant factor in the vertical loads on the structure, especially in hilly country. This is in addition to the dead weight of wires and insulators.

From the data tabulated it is possible to prepare the stringing chart for each type of conductor. This is one of the most useful graphic diagrams, and consists of a series of curves for a given wire, showing the variation of tension in the wire with the span length, one curve being drawn for each temperature. While it is realized that the wire will be loaded up to its maximum tension of 40 per cent., the ultimate load when full wind and ice are on at minimum temperature, the tension under ordinary conditions of weather is considerably less than this, and is the less the greater the span. Stringing curves are intended to show the tension and sag under stringing conditions, in other words, in calm weather, and these values will be tabulated for the use of the field crew in installing the wire. One of the facts shown by the chart is that it is very much easier to pull in the long spans than the short, especially in cold weather, due to the lower tension. Moreover, the difficulties of unbalanced loading between adjacent spans are considerably less if the spans are long, so that less difficulty is realized from the excessive deflection of suspension insulators toward the longer span in cold weather. For example, by reference to the illustration (Fig. 79) it will be seen that with two adjacent spans

of 1,400 and 1,600 feet there will be a maximum unbalanced tension of only 30 lb. at minimum temperature. But with two spans of 600 and 800 feet—the same difference in length—there will be an unbalanced tension of 800 lb. at 0 degrees

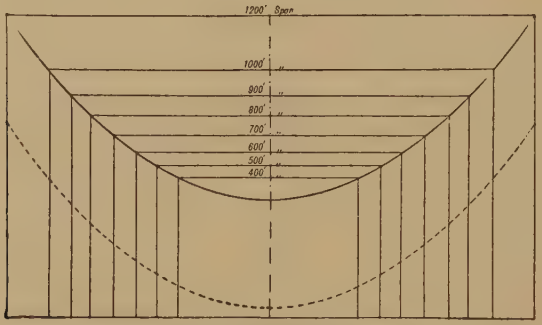


FIG. 89.—Sag template for 0.327 square inch aluminum-steel conductors.

which might lead to considerable deflection of insulators, although they would be in equilibrium at erection temperature in summer. As already seen in this chapter, the problem of unbalanced tension with diverse span lengths is one of the most embarrassing with which the transmission engineer has to deal. It is, therefore, very significant to note that the tendency toward longer spans is simplifying the problem. There is also another angle to the same question. While all parts of a structure or machine are designed for a given maximum load with a reasonable factor of safety, the behavior of the material will not fail to be influenced by the average load which it carries, and while according to the design assumptions it is perfectly immaterial whether the average load is 50 or 95 per cent. of the maximum, in practice there are certain exceptions to this, and one of them is insulator porcelain. Mechanical tension long sustained, although considerably below the safe limit, has been found to precede electrical breakdown. Notwithstanding, therefore, that a high-strength dead-end insulator would have a mechanical

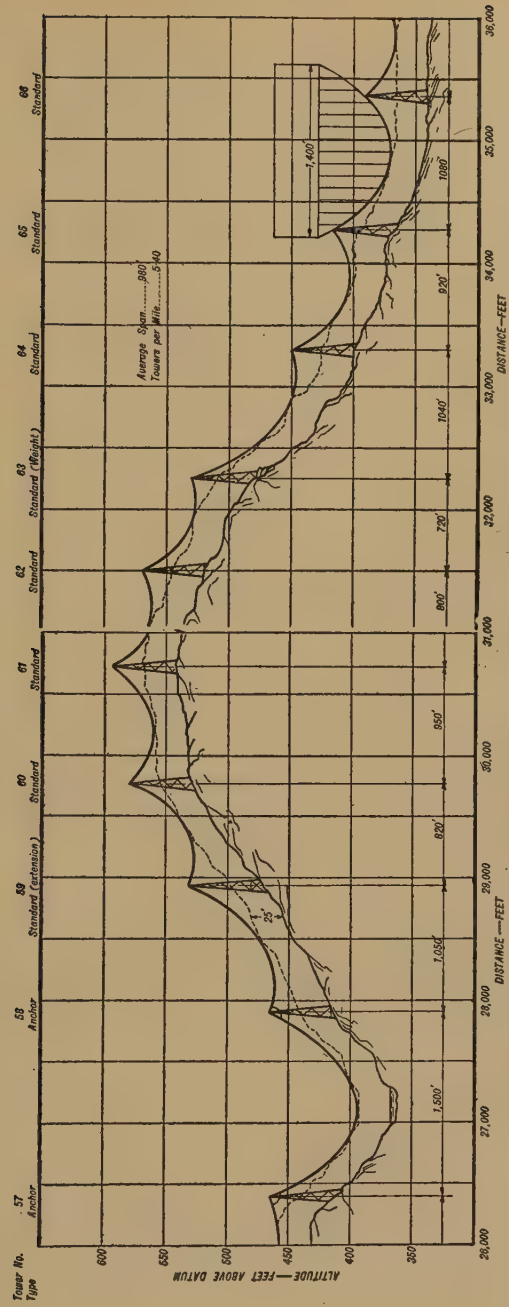


FIG. 90.—Section of actual transmission line profile, showing use of template for locating towers.

ultimate strength of 18,000 lb., it would be imprudent to carry a service load even of one fourth this value continuously.

Sufficient information is now available to prepare a template as described on p. 200, and to locate the towers on a profile of the line. Such a profile is reproduced in the figure herewith, being a section of tangent or straight line nearly two miles in length embodying considerable changes in grade. It will be noted that the horizontal scale is just ten times the vertical. A dotted line is drawn 25 feet above the ground surface to indicate the clearance of the lowest point to which the conductor may reach. The height of the standard tower to the lower conductor support is 50 feet, allowing for the length of the insulator. In setting the template on the profile, therefore, the lowermost point should coincide with the dotted line, and the wire should be drawn through this point and extended on each side to a point 50 feet above the ground. In the figure the template for aluminum-steel wire 415,000 cir. mils area has been used, with the result that an average span length of more than 980 feet is attained. With a conductor of lower tensile strength it would have been difficult to string with spans as long as this; moreover, it would have been nearly impossible to locate the supports so that uplift points were avoided. In the present instance a certain small amount of uplift will be experienced at Tower 63 in cold weather, and a weight of 200 lb. is attached to each of the insulator clamps in this location. Tower 59 requires a 10-foot extension, owing to its location, as it is necessary here to bring the wire up to a point 60 feet above ground. Towers 57 and 58, at the stream crossing, are the only anchor towers in the section, and their use eliminates troubles due to insulator swing toward the adjacent shorter spans. It will be seen from the profile that the arbitrary selection of a given " economic span " is virtually useless, because in average country no two spans are similar. The span actually determines itself after the various mechanical constants have been worked out and applied to the profile.

Whilst the illustration covers only about two miles of line,

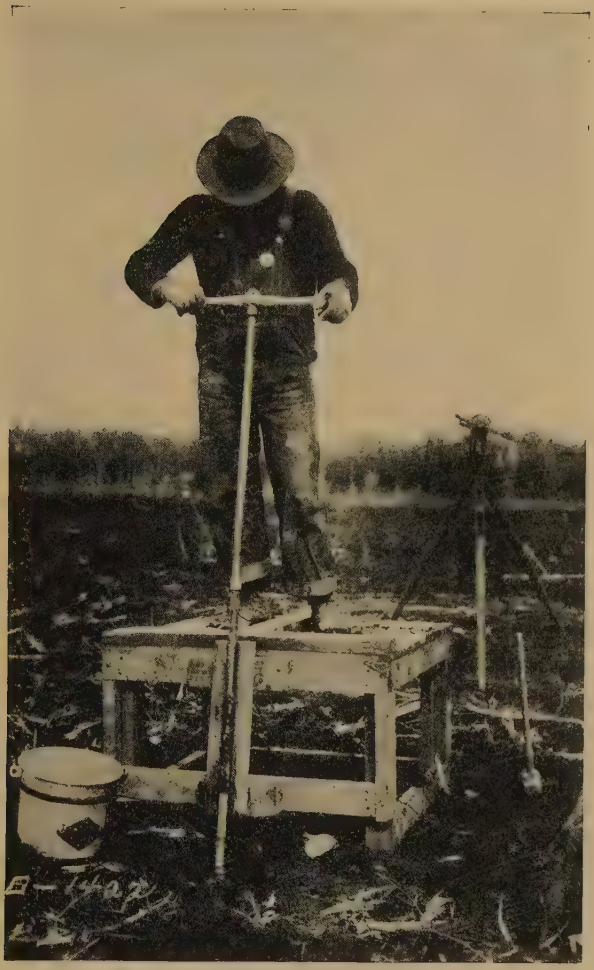


FIG. 91.—BORING THE HOLE FOR SETTING A MALONE CONCRETE ANCHOR.

[*Facing page 230*

FIG. 92.—HOISTING TOWER BY USE OF A MOTOR-DRIVEN UNDERSLUNG WINCH.

[*Facing page 231.*

it is understood that the template and profile are used in the design office to cover the entire route of the line. As already mentioned, a complete study should also include the comparison of different tensions in the line wires. The present calculations have been based on a maximum working stress of 40 per cent. the ultimate strength. If a figure of 50 per cent. were adopted, the spans would be longer, and the individual towers heavier; with 30 per cent. tension the contrary would be true. As a matter of practical experience, it is found most economical to work to the higher value of tension in mountainous country, and to the lower value where the land is flat. Of course, every transmission line is divided into sections, each section being designed with the mechanical constants most suitable for the location.

CHAPTER V

CONSTRUCTION

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Surveys.—Both preliminary and detailed surveys are necessary when a transmission line is planned. The former is mainly a reconnaissance with the object of establishing the general contour of the country, presence of rivers and streams, swamp or marsh land, hills and uncleared ground on the line of route, as well as in a general way the degree of cultivation of the country. This preliminary survey (or, more properly, selection of the most satisfactory route) is now not infrequently performed by aeroplane, which method is of particular value in mountainous country, especially where Government surveys are inadequate or altogether lacking. Aerial photographs are taken and pieced together; the line is then drawn in sections as straight as practicable having regard to physical and other local influences.

Such aerial maps show in most striking fashion the degree of cultivation of the ground, the nature of the crops raised, the location of farm and other buildings and yield information which is of inestimable value when treating for wayleaves. In a preliminary survey over the ground the power interest is to a certain extent committed to a given route, and this sometimes encourages inflated valuations on the part of the freeholders. By an air survey such action is forestalled, and the proposed route,

together with two or three alternatives, can be mapped out before the information becomes public.

A detailed survey can then be made with the object of securing wayleaves where necessary, noting superficial geological data, such as the nature of the top soil and its ability to hold tower footings. Where Government data are not available, of course, it is necessary to take levels, compile heights and distances, and note the width of streams and valleys which will exceed the normal span length of the line. In actual practice it is generally considered prudent to take levels throughout the line whether a Government survey exists or not, so that the steel requirements can be accurately estimated. The information derived from the surveys, in the form of maps and profiles, is turned over to the designing office, where tower spotting will be proceeded with.

In one sense a transmission line survey differs radically from that for a railway or highway, in that it is not desired to reduce the grades, but rather to seek, within reason, the most hilly route. Obviously, stringing wire across the hilltops in undulating country is attended with the advantage that the number of supporting structures is reduced. Unless the grades become very long and steep, the problem is actually simplified by carrying the line across rough country. In such locations, too, the ground is usually satisfactory for tower footings, whereas low-lying country is apt to be sedimentary in formation, water-bearing, and otherwise uncertain in character. In the Western United States the problem of alkalinity is a serious one, but the territory involved is generally too wide to avoid. It is, however, true to say that the soil becomes far less permeated at higher altitudes.

Whilst the grade may be variable, it is important that the alignment should have as little change as possible. In some instances high-tension tower lines have been built as long as 100 miles without any change in the horizontal alignment. Obviously, this reduces the cost of survey and construction and also improves the operating features by eliminating dead ends

and strain insulators. Such a survey is, of course, impossible in a highly industrial country, but it represents the ideal condition. The survey will also endeavor to locate the line approximately parallel with a road or railway throughout its length, if possible. Access to route for distribution of material will be considerably facilitated and the construction costs reduced. If this is not done, considerable excess right-of-way will have to be acquired for the purpose of making roads. A parallel main road offers good opportunity for patrolling the line during operation, either on horseback or by automobile.

The route may be modified due to experience with electrical storms. Generally, in a country which is frequently visited by lightning, such visitations will be found to have remarkably local habits. It is distinctly untrue to argue that "lightning never strikes twice in the same place"; as a matter of fact, certain small areas are visited by almost every storm, due to some unexplained geological reason, and it is often practicable to lay out the line so as to avoid them. The operating records of telegraph and telephone companies in such territory will be of considerable value in forming judgment on this matter.

In the final survey the levels at railway and highway crossings must be carefully recorded, in order that sufficient clearance be allowed on the office profiles. Similarly, the heights and locations of telegraph or telephone wires and the exact proximity of all structures, whether permanent or temporary, must appear in the survey sheets. In general, no habitable structures are permitted on the right-of-way, and if not avoided, they must be acquired and marked for destruction by the clearing party. Where a wide river is crossed, it is sometimes possible to secure the privilege of carrying the line on crossarms mounted at the side of a bridge structure. This is often done in the case of a steel bridge, and, in view of the cost and difficulty of stringing and maintaining a long crossing, the privilege is usually well worth a satisfactory annual charge from railway or highway authority.

Clearing.—In the comparison of alternative routes, the se-

lection will often lie between cultivated and virgin forest; in the former case there will be little or no clearing, but the cost of right-of-way and the indemnity for crops destroyed during construction may be considerable. In virgin country, on the other hand, the wayleaves will cost relatively little, but an appreciable amount must be expended upon clearing. The width of belt will vary considerably, but for a double-circuit tower line three times the length of a crossarm is not unusual for the entire width of right-of-way through forest, where falling trees might foul the line wire. If the longest tower crossarm is 25 feet, an additional 25 feet will be allowed on each side of it, making a width of 75 feet. This will generally be ample to prevent tall trees being blown into the line. On the other hand, it is

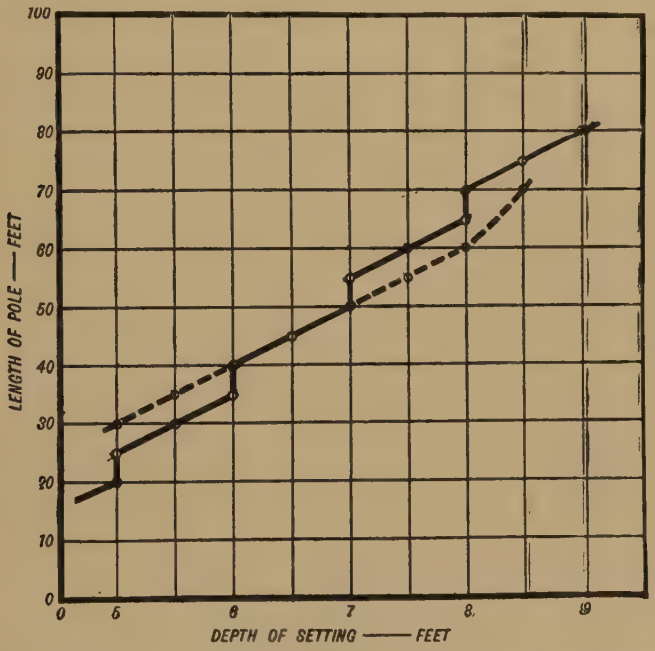

FIG. 93.—Appropriate depth of pole foundations according to two authorities.

better economy to build the same line with a 50-foot right-of-way, and to secure permission to clear the timber 13 feet back of the fences.

In the case of the 132-kilovolt tower line built from Morwell to Melbourne by the Victorian Electricity Commission, it was considered prudent to clear a right-of-way 250 feet wide for the two tower lines running through timbered country. This very considerable width was dictated by reason of the hazard from forest fires and the low cost of right-of-way.

Clearing is commonly done by local contract, and where a private right-of-way is secured by the power company, the value of the timber will frequently pay for the cost of clearing. Generally the trees are cut, logs sawn in a portable mill and removed, and the brush- and cord-wood burnt. It is not customary to grub the roots.

In cultivated country clearing the right-of-way is generally confined to the simple operation of cutting a path about 4 feet in width through hedges and fences, and installing gates. Plank or trestle bridges may have to be built across streams and gullies, and where there is no parallel main road all such gates and bridges must provide for the transport of line material.

Following the clearing of the right-of-way, a party will go over the route and stake all the tower locations, using the office maps, on which all the towers are spotted. Each stake is driven in the center of the tower base, and each is numbered corresponding to the tower itself. Four additional stakes are driven to indicate the alignment and the center lines of the tower base.

Setting Foundations.—The foreman of the excavating crew will set out the four locations for footings from the center and side stakes, using a tape or a wood gauge. In digging holes for the footings it is essential to disturb the ground as little as possible; in other words, the hole should be dug at the correct angle and depth, but with the smallest practicable diameter. If the footing is to be a simple ground stub or a tripod, it is, of course, necessary for the hole to be slightly larger than the steel foundation grillage to be inserted, which may be from 2 to 4 feet square. To dig a hole at the correct angle 8 feet deep and of these dimensions requires no small skill in shovel work, as well as care in removing the loose earth; a number of tools are avail-

able, however, which help to accelerate and make the work easier. For heavy dead-end or angle towers or for high crossing structures a special concrete pyramidal base will be used for each main post footing, and holes are dug of the necessarily large size, the wood forms inserted, and the stub angle set in place and held by a steel template at the ground line. The mix is then poured into each of the forms and left several days to set before the forms are removed and the holes backfilled. In the regular earth footing, a carefully-tamped backfill takes the place of the concrete, and conscientious skill and judgment are required in a greater degree. When the four ground stubs (each with its steel grillage or foundation plate) are set in the holes and the tops bolted to the standard template, it is important in the first place to see that each has a firm and level base, so that subsidence of any of the footings need not be feared. In some instances a concrete floor has been poured at the foot of each hole to secure a level bearing surface. Having effected this, any large stones available may be used to wedge around the lower end of the ground stub angle to assist in anchoring against lateral movement. Backfilling and tamping may now be done, using one shovel man to four tampers so as to ensure the earth being packed solidly right up to the surface. In general, ground stub footings ought to be allowed at least one week for the earth to consolidate before imposing upon them the strain of tower erection. Any form of concrete footing, of course, will require three times as long.

The simplified form of concrete foundation known as the Malone footing has already been described under the heading of Tower Foundations. The use of this device effects considerable constructional economy, because one man can excavate the holes with a 5-inch post-hole auger and a timber frame with a guide to hold the auger at the correct angle. Not only is the minimum yardage of concrete required, but this same quantity is most effectively used, and one of the most considerable merits of all is that no forms are required. Prior to the use of this general type of footing (using a bulb-shaped hole shot with

dynamite) the advantages of concrete foundations were everywhere appreciated, but the transportation of the necessary wood or steel forms was a serious drawback, and effectually prevented concrete being widely used, especially in rough country. Now the condition is quite the contrary, and the Malone or " bulb " footing requires no forms as compared with the older type of concrete foundation; it also uses much less steel than the regular ground stub.

The structural steel template, to which the stub angles are bolted at their upper end and set to line and grade, is a clumsy but most important piece of apparatus, as if it is not carefully set or is prematurely removed the levels may be impaired, and the tower will be out of plumb when erected. In a newly-poured concrete footing there is a possibility of the stub angle subsiding after removal of the template, so to avoid this a ½-inch steel rod is passed horizontally through one of the bolt holes at the upper end of each stub and solidly blocked up at either end.

In view of the extremely large towers now becoming common, this type of template is being dispensed with. A relatively simple device is used to set each individual stub at the required angle and the footings are lined up by the use of a level and transit.

In some locations in swampy country it may be necessary to sink a small steel barrel to act as a coffer for each tower footing. A number of heavy four-circuit steel towers were erected some years ago by the Toronto Power Co. on the shore of Lake Ontario, this forming part of the route from Niagara Falls to Toronto. On this occasion a pyramidal wood coffer dam was made up with double-thickness 2-inch timber, and driven by a steam hammer to a level 10 feet below the bed of the lake. The sand and gravel were then dug out to a depth of 6 feet below the lake bottom and the concrete poured into the form, the latter being left in place as a permanent protector. A number of reinforcing rods were used in the foundation, and four long 1½-inch foundation bolts also were embedded in the concrete, extending out 17 inches for bolting down the shoe of the

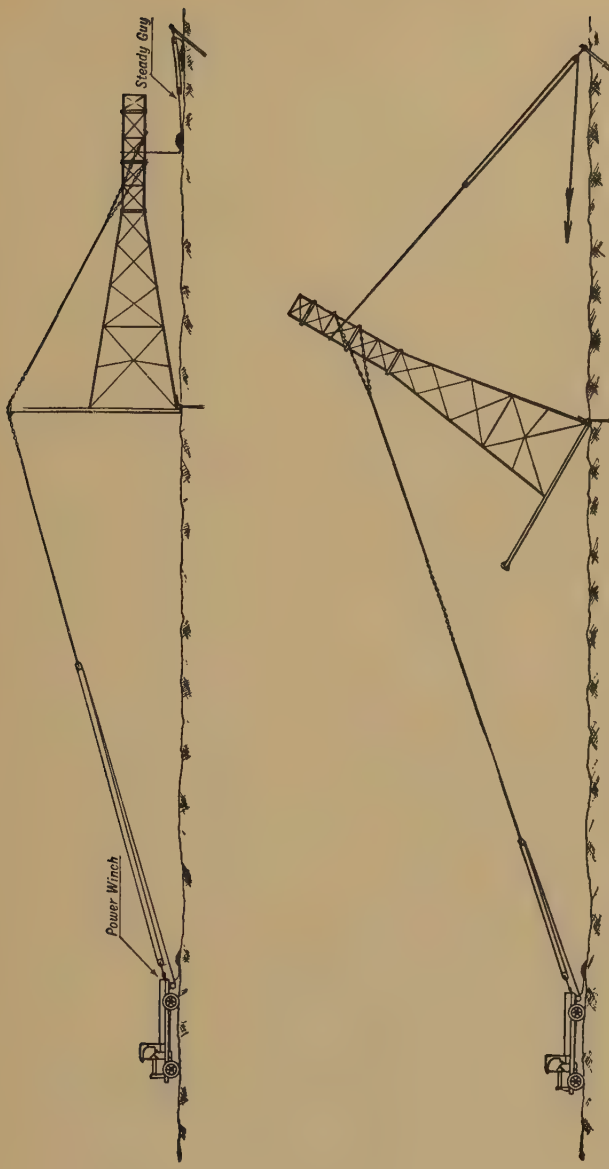

FIG. 94.—Method of hoisting complete tower with truck (anchored), underslung winch and shear pole.

main tower post. Loose rock was piled around each footing to form a pier for protection from storms.

For heavy crossing towers the foundations must be carried down considerably deeper than the above. For the 350-foot towers on the St. Lawrence crossing of the Shawinigan Water and Power Co. reinforced concrete caissons were employed, 7 feet in internal diameter and 2 feet thick. These were sunk in sections to a total depth of 40 feet (about 12 per cent. of the tower height), being excavated by a bucket, and finally plugged with mass concrete. The four foundations for each tower were then connected by reinforced concrete beams.

The foregoing references have related to footings set in ordinary ground or in wet soil. Solid rock is sometimes encountered, however, and in this case it is usual to level off the rock, drill it, and set in fang bolts, using cement grout or boiling sulphur. A shoe is made up of short lengths of heavy angle, which is bolted to the tower post and also to the foundation bolts. To secure accurate levels it is generally the most satisfactory to pour a concrete base a few inches thick for each shoe before drilling the bolt holes.

A still more simple method has been used with success, that is, to take a stub angle about 3 feet long and to cut off one web for about 2 feet of its length, forging down the other to form a round section about 1¼ inches diameter. The rock is drilled about 1¾ inches, and this rod section is grouted in solid, leaving the angle portions projecting, to which the tower posts can be bolted in the conventional way.

Erecting Towers.—While the present treatise deals extensively with the steel tower transmission line, it is not desired to overlook the fact that the wood pole still has valuable economic advantages, and it is probable that in the majority of cases timber construction will show a saving both in respect of capital, construction, and all other charges for lines built to operate at 66 kilovolts or less. In the matter of construction, however, it is not necessary to particularize, because the same factors apply to both types of structure. The line must be surveyed, right-

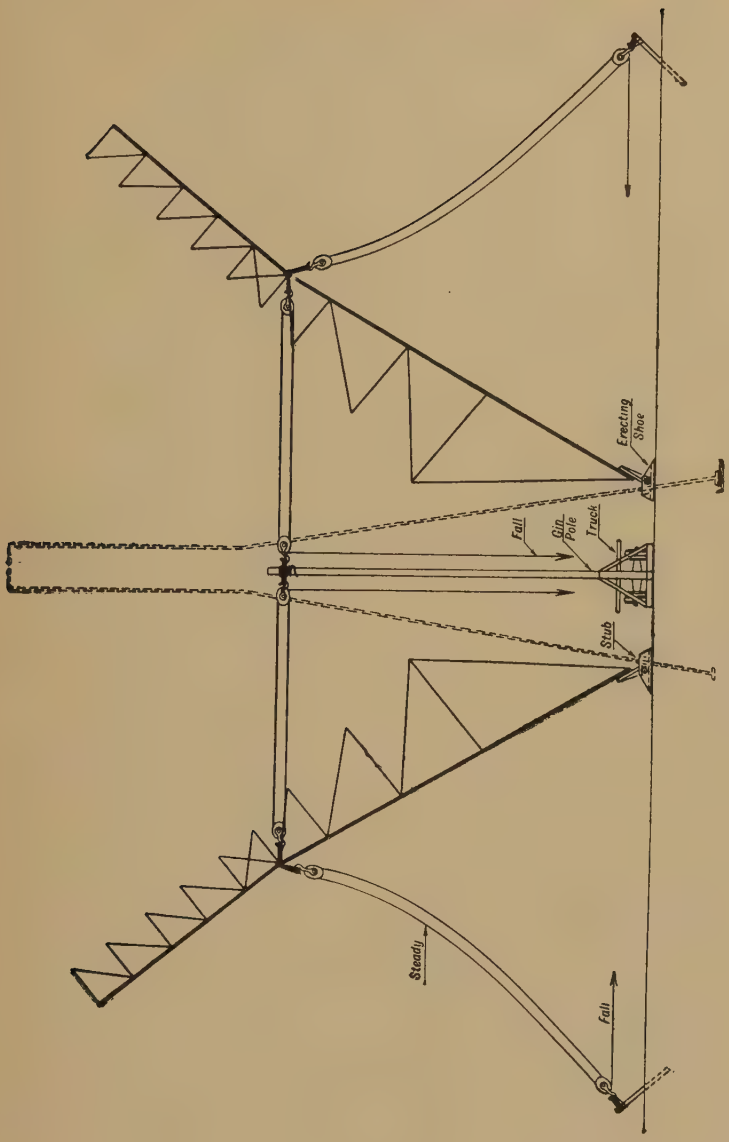

FIG. 95.—Method of hoisting tower in two halves.

of-way secured and cleared, pole locations spotted, and holes dug. Since the spans are limited to about 400 feet, particular account must be taken of the profile. Poles are hoisted and set by a derrick rigged on the end of a motor truck, and are tamped by hand. Wire stringing and subsequent operations will be the same for pole as for tower lines. In tower-line work, however, there is a good deal of diversity in the methods employed, and the financial success of the entire power undertaking is largely dependent on the rapidity and efficiency of line construction. The interest charges during the erection of a line 100 to 200 miles long will amount to a seriously high figure if any contingency arises to delay the progress. Lack of efficiency in labor and supervision may reduce the average advance on the work from 1 to only ½ mile per day. If it is assumed that the investment tied up in a 200-mile transmission line is $4,000,000 (a not improbable figure), then the increased charges at 6 per cent. due to the slow progress will amount to more than $132,000 for interest alone, setting aside the additional labor, amortization, and other charges. Speed is, therefore, so essential that very advanced methods of setting towers and stringing wire are now commonly adopted. For building the tower structures two methods may be employed, according to the nature of the terrain and the weight of the towers: (*a*) the structure may be partially or wholly assembled in a prone position and raised by lifting tackle to the perpendicular, or (*b*) it may be erected piecemeal in the same manner as a steel building or other permanent structure. In either case, the tower sections are carefully distributed along the route by motor truck, the requisite numbered bundles, together with their bags of bolts, crated insulators and hardware, being deposited at each staked tower location. All tools and equipment will be brought to the site by the tower crew, using a motor truck or lorry in good country, and horses, mules, or coolies under other conditions. In mountain country mules form the usual means of transportation, and foresight must be exercised in the designing room in order that the respective sizes and bundles of steel shall

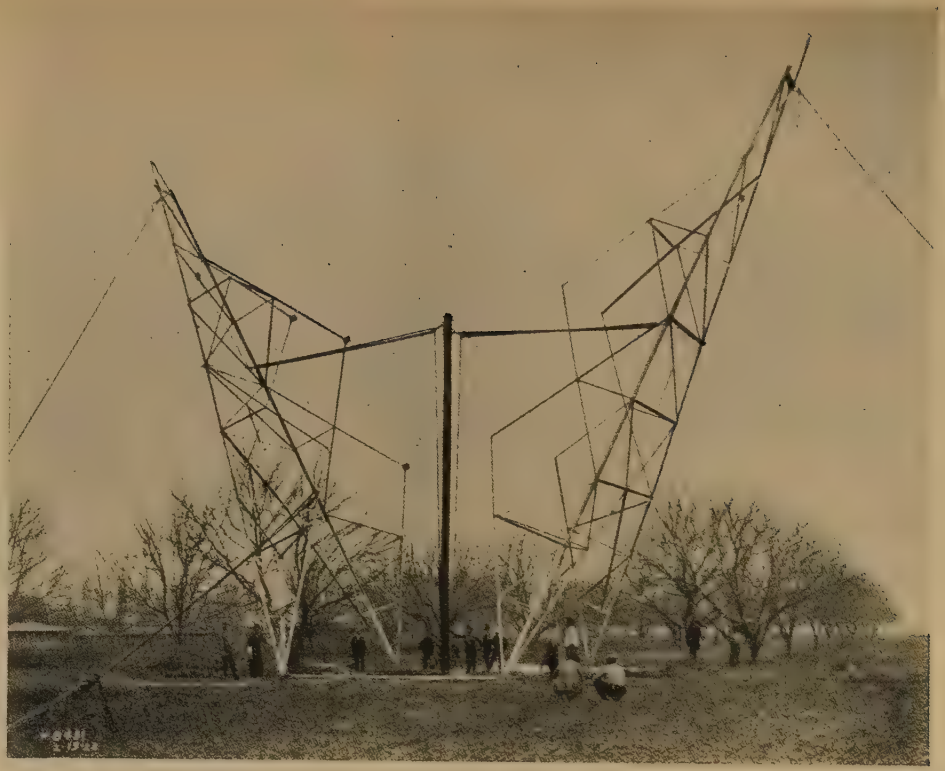

FIG. 96.—ERECTING TOWER IN TWO HALVES BY USE OF GIN POLE AND TRUCK WINCH (SOUTHERN CALIFORNIA EDISON CO.). [*Facing page 242.*

FIG. 97.—PORTABLE HYDRAULIC JOINTING PRESS AND PUMP FOR USE IN THE FIELD WITH ALUMINUM CONDUCTORS (JOHN ROBERTSON CO., BROOKLYN).

[*Facing page 243.*

not exceed the mules' capacity. "Other countries, other manners"; in Peru the beast of burden is the llama, who has a clearly defined conception of the maximum permissible load which may be packed, and no persuasion will compel him to carry more. In Japan the structural material must thread several miles of narrow tortuous village streets on a hand cart, and the length of the members is, therefore, limited.

Using method (*a*), one face of the tower will be entirely assembled, blocking it up level to avoid distortion due to inequalities in the ground. Side bracings and additional main posts can then be bolted on, finishing off with the crossarms and insulators. The structure is very rapidly assembled in this way, because of the large crew which can work on it at one time.

It is now necessary to hoist the finished structure, which will have been assembled with the lower end of two of the post angles in close proximity to the foundation stubs. These post angles are spliced to the foundation members by a short length of fish angle, which has the outside corner carefully rounded so as to fit into the fillet of the main angles. From eight to twelve bolts will be used in each of these joints. Before raising the tower, a hinge must be provided on which these posts can turn through a right-angle on the tower as raised. For this purpose, a 6-inch pipe, securely anchored and jacked up with timber, is sometimes used as the axis, being anchored to the ground stubs. Two forged U-shaped shoes fit over the pipe and form the hinges; they are thoroughly greased and provided with extensions, which are bolted to two of the tower posts. Before applying the tackle, the open end of the bottom panel of the tower should be temporarily braced with lengths of angle section to avoid deformation. Either a gin pole or shear legs may be used for the actual hoisting operation; the gin pole being rigid, must be very securely guyed, and for this reason the shear legs offer a more convenient method, except where the tower has been only partially assembled. Timbers of about 45 to 50 feet long are used having a diameter not less than 6 inches at the top, the spread at the base of the shear legs being

from 15 to 20 feet. In recent installations the weight of the towers has become increasingly heavy, and steel pipe has taken the place of the timber shears. The lower ends of the shear legs are supplied with shoes, which turn on the same pipe as the tower post hinges. Lifting tackle consists of 2-inch steel wire rope for heavy towers, connected by means of a bridle to a chain around the basket of the tower near the lower crossarm. The cable passes over the sheave or groove at the top of the shear legs, and at this point is sometimes bridled to a length of chain, which rides on a pin in the groove and prevents slipping. It is carried back from 200 to 250 feet and anchored through a 12-inch triple or quadruple steel block and tackle. The conventional anchor in good ground consists of three or five or more wrought iron pins, each 2 inches diameter by about 5 feet long. These are driven into the ground in a triangular plan and connected by a chain which will distribute the pull, and to which the block and tackle are connected. If the soil is not sufficiently solid for this type of anchor, it may be necessary to bury a " dead man," consisting of a log about 1 foot diameter and 6 feet long, to which a cable and eye are connected so as to project above the ground line.

Patent screw anchors are convenient to use for reasonably light construction, but cannot be relied upon for the reaction necessary to raise a heavy tower.

Before beginning to hoist, a back guy and two side guys are attached to the tower so that it cannot get out of hand due to a high wind, hoisting too rapidly, or other reason. These guys may consist of ½-inch or ¾-inch flexible steel cable anchored to ground pins through a double or triple 8-inch block and tackle, with a lineman and helper to stand by at each.

For the actual hoisting the fall of the tackle is taken to a mule team, motor tractor, or to a special form of underslung winch connected to a motor truck. This device has the merit that the lorry with its brake set is generally heavy enough to form the dead end as well as the hoisting gear, and in this way all the time of making up a dead end is saved. Where the

ground is wet or very rough, the lorry cannot be used, but a Ford or caterpillar tractor is often found satisfactory. The caterpillar particularly has proved a marvellous adjunct to line construction in rough country, not only for hoisting towers, but for transporting material and stringing wire. A right of way thickly strewn with fallen logs has proved no obstacle to this type of tractor.

A team of mules or horses is the next best motive power, and with any of these devices from four to eight towers per day should be raised. In Japan, where man-power is abundant, it has been the custom in high-tension line construction to carry the tackle fall to a capstan, which is operated in the conventional way by ten or a dozen coolies. Owing to the very swampy condition of the paddy fields over which many miles of transmission are built, this method has been found unsatisfactory in many locations, on account of the difficulty of finding a secure foundation for the capstan. It is now more usual in that country to build up the towers in place, section by section, as described in method (*b*).

In view of the great height and weight of line towers as now designed, it is becoming common practice to assemble them in two complete halves, each lying transversely to the line; these halves are hoisted simultaneously into a perpendicular position and held by the tackles whilst the cross bracings are bolted on and the anchor connections made. Obviously, shear poles cannot be used in this case, being supplanted by a rigid vertical gin pole mounted in the center of the tower foundation, and guyed fore and aft. Since the load on the pole is balanced, little guying is required. Two sheaves are connected to the top of the gin pole and the hoisting lines carried to two triple sheave blocks in the usual way, or, alternatively, the tackle can be connected direct to the tower frames and anchored to the top of the gine pole, by which means a lighter hoisting line can be used. A back guy and tackle must be attached to each half of the tower so as to hold it while the bolts are inserted after hoisting. In the most recent practice a 2-ton motor lorry is employed not

only to transport the equipment, but to form a base for the gin pole, which is mounted on the rear end of the truck and swung up and braced into position when the vehicle has backed up into location at the tower foundation. The use of a truck predicates good ground, although in many parts of the country this equipment has operated with satisfaction even where the ground was soft or scattered with rocks. In favorable conditions an average of ten towers per day have been erected with this apparatus over a long stretch of country. This would correspond to a daily progress of 1½ to 2 miles under ordinary conditions.

Method (*b*) of tower erection connotes the raising of the structure member by member from the foundations, and is the only means which can be employed in mountainous or swampy country. A certain number of towers on any line will have to be built up this way. This process, however, requires the minimum amount of apparatus and *personnel,* and can be followed with satisfaction wherever progress is not all-important. The gin pole is the most important piece of equipment; it is mounted in the center of the tower base on a wood block foundation, and anchored with at least four steel guys. The heaviest members, the corner posts, are bolted to the foundations one by one and temporarily held in place by the diagonal bracings of the bottom panel of the tower. The gin pole will generally be from 40 to 45 feet long, and when this height is approached it must be hoisted to a new position, its base being hooked to a strut on the tower frame, the guys reset, and construction carried up to the topmost panels. Much of this work may be simplified if the tower is specifically designed to be erected by the "unit" method. Angle lengths can be devised so that the splices will be at convenient points, and a reasonable limit of weight should be set upon tower members.

By the unit method one tower per day is the usual progress, but with proper dispersion of the crews a number can be under construction at one time. There are two important advantages possessed by this method over that of hoisting. In the first

place, when the complete tower is assembled and pulled up into position, it is necessary for two or three men to ascend the tower and systematically tighten and upset every bolt in the structure. During the hoisting operation the jolting and straining of the structure loosens a number of the nuts, so that virtually every one has to be tightened twice over. In the second place, the destruction to crops, owing to the large crews, heavy trucks, and horizontal assembly, is very great and compensation correspondingly heavy. With the unit method of construction, once the material is distributed, damage is virtually confined to the actual area of the tower base.

One of the most vital factors in securing economy of construction lies in complete co-operation between the designing, fabricating, and construction departments. Maximum progress can only be obtained by the distribution of carefully assembled and numbered bundles of steel, together with all necessary blue prints for use in tower erection. In some cases considerable delay and cost have been incurred in the field due to the sections being punched in the shop without the use of proper templates. Bolt holes were found to be out of alignment, and a portable broaching mechanism had to be set up and operated at every tower location before the sections could be assembled.

Stringing Wire.—When the transmission line towers are assembled, the insulators are hung on the crossarms and everything made ready for the wire crew to string the cables. This is a work beset with difficulties, but means have been found to overcome most of them, so that at the present time it is possible to string wire on a line from 20 to 100 per cent. faster than towers can be erected. For this reason, the tower crews work well in advance of the wire-stringing party to avoid conflict and delay.

It has already been seen that most power lines are double-circuit, involving six wires, and it is customary to run out and pull up three wires in unison. The wire is delivered from the cable works on drums containing predetermined lengths, and these are distributed along the line in threes, spaced according

FIG. 98.—Method of pulling up wire with a running line and winch.

to their lengths. A motor truck carrying the stringing crew up to the starting point will also carry three timber reel stands, or in some cases the stands may form part of the structure of the vehicle. In such a case two methods may be adopted: either (*a*) the ends of the wire may be temporarily anchored and the truck carrying the drums on their spindles will drive along the right-of-way, unreeling the wire as it goes, or (*b*) the reel stands may be set up on the ground and the wire pulled out by a team of horses, caterpillar tractor, or by a winch. Clearly, the first method is ideal where the ground is favorable; in no case is the wire pulled over the earth, nor is any delay incurred in hoisting the wire up to the snatchblocks, which are hung on the crossarms, because this can be done whilst the truck is in progress. On the other hand, over rough ground it becomes very difficult to control the rate of paying out, and the heavy drums may become unmanageable. Turning to method (*b*), the chief problem to solve is the avoidance of damage to the wire due to friction with the ground surface. On every tower crossarm a specially-designed hardwood block is hung with an 8-inch sheave mounted on ball bearings. This block carries the wire at the same level as the insulator clamp, so that transference can be easily effected after sagging. As soon as the team or tractor drawing the three wires yoked together arrives at this point, it pulls a little ahead of the tower and halts to permit each cable in turn to be hoisted up and placed in its block, after which progress is resumed. However, it is obvious that the wire will sag to the ground between supports, and care must be exercised that it is not dragged over rock or stones. To cross a wire fence, highway, or other obstruction it is common practice to erect a timber stage over which the wires can ride. If timber has been felled along the right of way, it is a good plan to leave the logs lying, so that the wire can be pulled over them without damage. This artifice sometimes renders swamp country passable for a caterpillar tractor. Especial care must be taken in pulling wires uphill, where it is literally impossible to keep them off the ground and where the ground is liable to be unusually stony.

The use of mechanical power has led to more skilful handling of the wire. Assuming that a 6-h.p. gasoline-driven winch is to be used to string a section of line which may be from ½ to 2 miles long, at one end are located the drums of cable mounted on their spindles, and at the other the pulling engine. Between the two the " pulling line " is strung loosely through the snatchblocks. This line is a flexible galvanized steel wire rope of ⅜ inch to ½ inch diameter, and is usually made up in lengths of 800 feet for convenience, with bridles to ensure easy connection and disconnection. After running out, one end of the conductor is laced out and served around this line so as to make a solid connection which will take a strain. The other end is given two or three turns around the winch nigger head, and all is ready to pull out. As the greater part of the section may be out of sight of the winch operator, it is necessary to run a telephone line along the route so that he can be instructed when to start, slow up, or stop hauling. If the serving from the pulling line to the cable is properly made, there need be no seizing in the snatchblocks, and rapid progress can be made. As soon as the complete length of conductor is pulled out, the pulling line can be disconnected and carried back ready for the second reel. In rough country it may be better practice to yoke the three conductors to the pulling line, and to haul them out in one operation. This necessitates stopping the winch by telephone signal as each tower is reached so that the cables may be placed on the sheaves. In some locations in particularly difficult country it is found more satisfactory to set up the drums alongside the winch, and to pull the pilot line " out and home." Obviously, in this case the pulling line must be double the length of the section, and special care must be taken in anchoring the snatchblocks on the last tower, as they may have to take an appreciable load. The combination motor truck and underslung winch used for tower hoisting can also be employed for this work wherever the right-of-way permits, but it is more usual to employ a stationary engine in mountainous country, and a Ford tractor or caterpillar elsewhere.

When a sufficient length of wire (about two miles) has been run out, it is usually left hanging free for two or three days, after which it is necessary to strain it up to working tension and dead end. This will be done at a dead-end tower, if available. Assuming the farther end of the wire to be solidly anchored and that a dead-end tower occurs at the near end, the snatchblock is mounted on the end of the crossarm, and the string of strain insulators and clamp are also suspended from it, while two or three linemen are on the crossarm ready to snub off the cable as soon as it is up to tension. The cable is carried over the snatch-block to a point about 100 feet ahead, where the snubbing tackle (consisting of triple blocks and ⅜-inch steel cable) is connected on with a heavy forged "comealong" and a dynamometer. The tackle is anchored to a patent guy anchor, a "dead man," or to the temporary anchor pins, and the fall is carried around the nigger head of the pulling engine, which is then thrown into low gear. The wire is strained up slowly, and

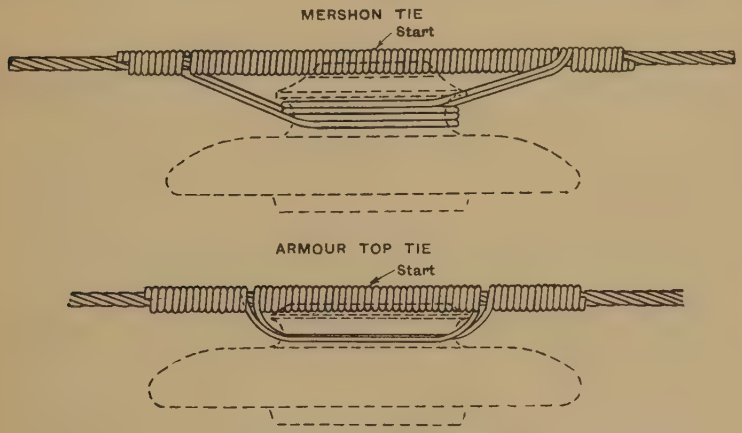

FIG. 99.—Two methods of tying conductor to pin-type insulator.

when it reaches the predetermined dynamometer reading it is held for about four minutes or strained up to about 20 per cent. higher tension, if possible. This short period enables the strands to adjust themselves to the load over the entire length of section.

In a recent installation the aluminum-steel conductors were pulled up to the elastic limit of 18,000 pounds and this tension held for three minutes. The wire was then slacked off to the correct stringing tension. Obviously, powerful engine and very secure methods of anchoring were necessary to effect this. The advantages secured, however, are that the characteristics of the composite cable are fully developed and an additional degree of safety is secured because the load imposed on the wires during stringing is probably in excess of any subsequent loading due to weather conditions.

With relatively small sizes of cable it is important to mark the elastic limit with red paint on the dial of the dynamometer. The tension is then let down to the required figure, and the crossarm men are signalled to clamp off. As soon as this is done, the tackle and comealong can be removed and the other two cables strained up in the same way. The sag for all the intermediate spans can then be adjusted by pulling the wire through the snatchblocks until it hangs with the required dip. A small wood crossbeam is attached horizontally to the tower frame at the point corresponding to the lowest point of the wire, and where the spans are long is provided with a telescope. In sighting across to the corresponding target on the adjacent tower, the sag can be closely adjusted by signalling to the crossarm man whether to raise or lower. Both tensions and sags are derived from charts prepared in the office, and the field crews are expected to work to these with an accuracy of 2 to 3 per cent.

In pulling up very heavy aluminum-steel cables to a high mechanical tension a special precaution is sometimes taken to pull on both the core and the envelope, otherwise the aluminum strands may be dragged out and damaged for a considerable length when the strain comes on. The method is to use two comealongs or bolted clamps joined by a flexible steel strand from six to eight feet long. The aluminum is cut off to expose about one foot length of the steel core; one clamp is attached to this and the other carried around a sheave and attached to

FIG. 100.—JOINTING HEAVY ALUMINUM-STEEL CONDUCTOR IN THE FIELD (HYDRO-ELECTRIC POWER COMMISSION OF ONTARIO), SHOWING ALSO METHOD OF SPLICING STEEL PILOT LINE TO ALUMINUM-STEEL BEFORE RUNNING IT OUT.

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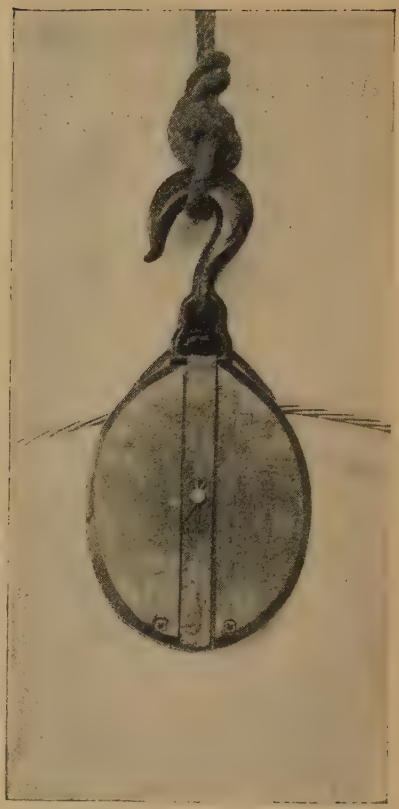

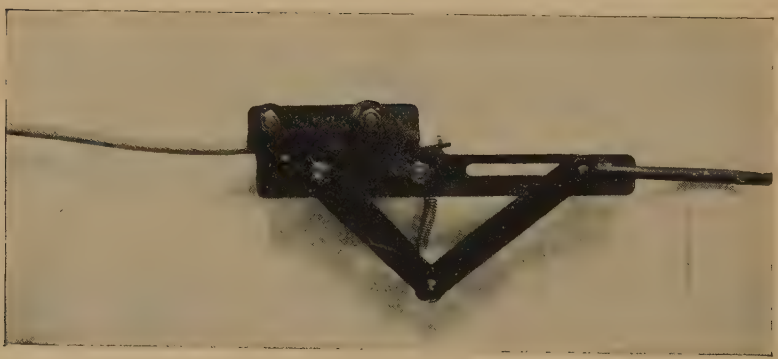

FIG. 101.—CABLE-STRINGING BLOCK WITH LIGNUM VITÆ SHEAVE.
FIG. 102.—FORGED STEEL COMEALONG CLAMP FOR 10,000 LB. TENSION.

[*Facing page 253.*

the aluminum envelope. By this means the sheave acts as an equalizer and the pulling tackle is coupled to it.

Sagging the wire is distinctly arduous work, falling upon the linemen who are located on the tower crossarms. Beginning at the first tower from an anchor point, the wire has to be pulled through the block until the sagger who is sighting along the line signals with a white flag that the deflection is correct. When all the spans in one section of line have been sagged, at a given signal every lineman will bolt his wire into the insulator clamp, using a triple block or a turnbuckle to hoist the wire out of the snatchblock.

As the modern transmission line is designed with very few dead-end points, it is often necessary to form a temporary dead end when straining up. With relatively small sizes of cable it is safe to anchor direct to the crossarm of the suspension tower, because the stringing tension is usually not more than 25 to 35 per cent. of the maximum designed cable stress. It is, however, a wise precaution to back-guy the crossarm to a " dead man " or other anchor when doing this. Ordinarily the cable is carried over the snatchblocks in the usual way, and then dead-ended by seizing it to the main posts of the next tower at the ground line. In straining up this way a downward component of the tension will be exerted on the crossarm, but as the span is usually not less than ten times the tower height, this load is not serious.

Composite aluminum-steel cables require a little different handling at a dead end, due to the fact that the clamps are designed in two parts—the front to anchor on the aluminum, and the back on the steel. When the conductor is strained up to tension, the crossarm crew (working on a suspended platform) will attach a comealong or bolted clamp, and seize it to the tower crossarm. The winch and tackle can then be slacked off and used on another part of the job. Meanwhile, the tower crew will attach the aluminum clamp at its correct position on the cable, and connect it up solid with the insulators and links back to the tower crossarms. It is now possible to remove the

temporary seizing, to cut the entire cable at a point under the crossarm, and to unlay the aluminum strands back as far as the clamp. The steel core so exposed is cut to length, laid in its portion of the clamp, and bolted down, leaving only the aluminum wires to be stranded up by hand and carried around to

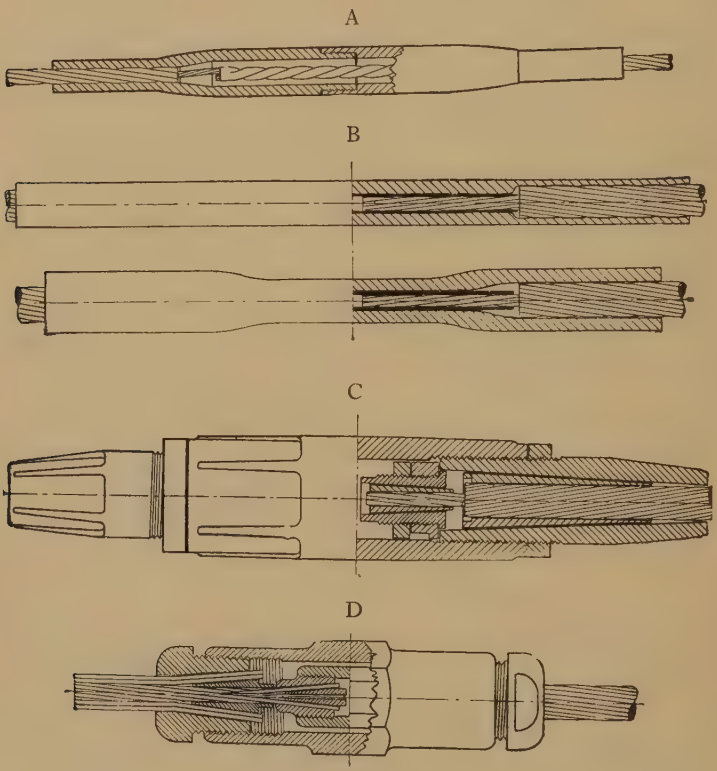

FIG. 103.—Four types of joint for composite cable. (A) American torsion-compression. (B) Heddernheimer compression joint. (C) A.E.G. conical seat joint. (D) Pairard joint.

the corresponding clamp on the farther side of the tower. Some erectors believe it desirable to clamp off the steel core before the aluminum. This can be done if the comealong for the temporary seizing is carried out about 8 feet from the tower. Any manipulation can then be performed on the slack portion of the cable.

Jointing.—When the entire contents of a reel have been run out, the free end of the wire must be spliced to the end of the preceding section. In virtually all positions where strain is to be carried a mechanical form of joint is used, dispensing with all soldering, brazing, or welding. The simplest method, in almost universal use for small and medium sizes of copper, aluminum, or the steel core of composite cables, is the so-called McIntyre sleeve. Section of this sleeve is oval, and the size permits the free ends of two cables to slip in and lie side by side for a length of from 2 to 3½ feet. The material of the sleeve corresponds with the conductors, except that it is usually annealed. A clamp with long handles is applied at each end, and the combination is twisted up by hand from three to four complete turns. The resulting joint is surprisingly efficient both mechanically and electrically; it is relatively immune from deterioration by corrosion, and is economical both of material and labor. Where the cable is somewhat large and stiff, the work of making the joint is rendered easier if one of the clamps be fixed and the other turned. Another precaution usually necessary is to use a split pipe clamped over the sleeve during twisting to hold it to shape and prevent bending.

The largest size of cable which can be spliced in this way is about 400,000 cir. mils copper, 650,000 cir. mils aluminum, and 250,000 cir. mils aluminum-steel. There is a possibility that larger conductors could be handled if a geared mechanical device were employed for twisting, but such has not yet been developed.

Aluminum possesses the property of plasticity under heavy pressure, and the compression joint, based on this principle, has been developed for large sizes of cable. A cast aluminum tube is used, bored to fit the conductor and having a length of 1½ to 2½ feet, with a wall thickness of ½ to 1 inch. Butting the cable ends together in this tube and squeezing it at intervals between the jaws of a portable hydraulic jack results in a very satisfactory splice. The jack and its accompanying pump have been developed to yield 100 tons pressure in a small convenient

size for use in the field, and the work is facilitated by a series of lugs cast on the tube at intervals, these lugs being pressed down flush with the tube. It should be noted that the cable section is not perceptibly deformed, but the metal of the sleeve is forced into its interstices. Several forms of joint have been developed using a tube and a mechanical tool for pressure, but most of these depend upon a " crimping " action, which deforms the cable and distinctly weakens it. A combination of the torsion or McIntyre joint and the compression splice is used for aluminum-steel cables. In this case the cast sleeve is made in two halves, screwed together in the middle. The operation of making up this joint is not difficult, being as follows:

(1) Cast aluminum sleeves are slipped over the respective cable ends.

(2) The aluminum strands are laid back, exposing the steel core, the ends of which are inserted in the oval steel tube and twisted up by hand.

(3) The aluminum strands are relaid and trimmed off so as not to overlap the steel wire splice.

(4) The two halves of the cast aluminum sleeve are screwed together over the steel wire splice.

(5) Using the hydraulic press, the lugs on the aluminum sleeve are squeezed to grip the surface of the aluminum cable and complete the joint. (Fig. 103A.)

The most recent form of composite splice dispenses with the McIntyre joint entirely, using simply a soft wrought iron compression sleeve for the steel strands and a single aluminum sleeve for the envelope. This is probably the most simple form of joint yet devised for composite conductors, the difficulty in developing it has been mainly due to the especially high degree of ductility necessary for the iron sleeves. In making up this joint separate dies are of course required for the core and the envelope splice but the same press is used. It is usual to insert a split aluminum tube by way of a filler between the steel splice and the aluminum strands. (See Fig. 104.)

This form of splice has the merit that it avoids the con-

siderable labor which was necessary to twist the hard steel strands in a large size of cable, and the resulting joint is more compact and experience will probably show it to be superior in almost every way.

On the Continent considerable use has been made of a conical clutch type of connector for all types of cable. A screwed

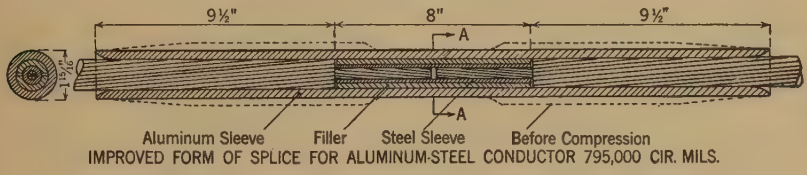

FIG. 104.—All compression splice for aluminum-steel cable.

sleeve is used containing a series of cones, over the surface of which the individual wires are splayed out and gripped by tightening up the sleeve. The basic principle is that of the conventional testing machine grip. Careful design is necessary to ensure that the conical surfaces shall not impose any local bend on the wires or that the grooving shall crimp the wire in any way. A larger form of joint on the same principle is employed to splice the heavy rope-stranded copper cables in use on one of the largest power networks of the Pacific coast.

In occasional instances it is insisted that the joints in a transmission line conductor shall be welded or brazed throughout. This is not difficult with copper or aluminum wires, using a blow-lamp and a suitable shield for the flame, but involves raising the temperature of the wire to the softening point, thereby reducing its maximum tension, in a practical sense therefore such methods are not to be recommended. Every joint must be made at a dead-end position, and the result is a very appreciable increase in the cost of the line for which there is no corresponding advantage. The best combination of mechanical and electrical efficiency is at present derived from the mechanical joint, and it is susceptible of still further improvement, whereas the welded splice is not.

It has already been mentioned in treating of dead-ending

aluminum-steel conductors that the cable is cut at the anchor points; a joint must, therefore, be made in the jumper loop connection at the anchor tower. For this purpose the parallel groove type of cast aluminum clamp is generally used. In this the wires are simply held between two aluminum castings clamped with three or four galvanized 5/8-inch bolts. It is sometimes customary to use an extra piece of cable in the jumper to avoid stranding up too long a length after the steel core has been taken out and snubbed. This makes a much neater job, but in such a case two connector clamps must be used, and it will be seen that they are in series. If the extra length of cable can be eliminated and only one break introduced in the wire, two connectors may be used in parallel, thus reducing the resistance to one quarter. This is a matter for careful consideration, because the connector clamp is not perfect, and the loosening up of such a joint has occasionally resulted in its burning right out and grounding the line. The tendency toward the elimination of dead ends, of course, reduces this hazard, but there is room for improvement in the design of connector clamps to preclude loosening due to mechanical vibration and thermal expansion. Owing to the joint having to be made at the tower crossarm, the mechanical splices already described cannot be used.

Most high-tension network involves the use of two types of conductor, and connections must necessarily be made between dissimilar metals. Where aluminum is the material of the line wires, connection must be made with copper at the transformer or switch terminals, and although no special problem is involved, it is necessary to design such joints with liberal contact surface, and to protect them as far as possible from corrosion due to atmospheric influences. Using the compression principle, an aluminum shoe can be pressed on the end of the cable, such a shoe terminating in a flat plate drilled with the necessary bolt holes. This can be bolted to the corresponding brass terminal, which is sweated to the copper transformer leads. Such a joint is ideal for the purpose, and it may be coated with bitumastic or

asphaltum paint as an additional protection. In the run of the line, copper and aluminum are not infrequently spliced together in an aluminum McIntyre sleeve, and, given a tube somewhat heavier and longer than normal, no trouble need be anticipated. Any simple means of filling the ends of the joint with compound should be adopted to keep out moisture. Such bimetallic joints should never be taped.

A splice between dissimilar metals must occasionally be made in the jumper loop at the dead-end point; in fact, this is the most usual, because the different stringing tensions of the two materials render it necessary to anchor off each one separately. In such a case the conventional connector clamp already referred to is modified in design and used for the purpose. Presuming that a copper cable is to be spliced to one of aluminum, the clamp will be cast in two pieces in aluminum and connected by galvanized bolts in the customary way; one of the grooves, however, will be lined with a copper shim, which is pinned or riveted into close contact with the clamp, and the copper cable is laid in this liner.

Whilst the problem of jointing copper and steel or aluminum and copper is one demanding conscientious thought and skill to preclude corrosion, it is not subject to the insuperable objections sometimes brought forward. A liberal design of the contact surfaces together with the protection of a coating of asphaltum paint at reasonable intervals have been proved by long experience to minimize or eliminate the troubles arising from galvanic action.

Personnel.—High-tension line construction calls for considerable organizing ability on the part of the superintendents, and for a high degree of individual skill on the part of the field crews. Complete co-operation is no less essential. A tower assembly crew bent upon speed may omit insulator suspension eyes, step bolts, or other details apparently insignificant in themselves, but which will hold up the progress of the wire-stringing crew when it arrives, and seriously prejudice the economic status of the work. Generally, notwithstanding the large number of

men employed scattered over a wide area of countryside, together with the non-productive costs of housing and board, the net labor costs do not amount to more than 15 or 20 per cent. of the total of material and labor. To attain such a proportion, however, well-trained crews and expert supervision are a *sine qua non.*

The following generalizations are, of course, subject to modification in many different conditions of labor, climate, and custom. So far as they are applicable, they may be said to relate to a double-circuit tower line built for 150 kilovolts, with spans of 700 to 1,000 feet, in undulating country, with good ground and subsoil.

Constant control of field work by the office is necessary to ensure that the work in various scattered locations will be adequately co-ordinated. For this reason the superintendent of line construction has his headquarters in the office rather than in the field. An assistant superintendent will be constantly on the job to receive reports daily from the various foremen, and to transmit them to the superintendent. The actual work falls naturally into about six divisions:

(*a*) Distributing material.
(*b*) Foundation setting.
(*c*) Tower erection.
(*d*) Wire stringing.
(*e*) Wire clamping.
(*f*) Cleaning up.

Distributing will generally require the services of a truck driver, checker, and three laborers to handle the crates of insulators, bundles of steel, wire drums, and hardware and to allot them to the respective tower locations. A good deal depends upon careful marking of the bundles and upon the intelligence of the checker, as misdelivery of part of the material may cost a very great deal in the shape of delay to the crews in the field.

Foundation crews will vary considerably according to the

type of footings employed. For the conventional earth footing using an angle stub and a steel grillage, an appreciable yardage of earth must be excavated, and not less than ten men will generally be necessary to dig the holes, set the grillages and stub angles to the template, level off, and backfill. The use of a post-hole digger set up on a motor truck and geared to the transmission offers an opportunity of dispensing with about one half the above crew. Such a digger must, of course, be capable of inclination to the necessary angle of the tower posts. The Malone type of foundation has already been described; in setting this one man can easily bore the four holes, using a post-hole auger, and the labor is much less than that required for a grillage footing. Alternatively, of course, the truck-driven digger is of advantage in this work. It has been found that only 1 per cent. of the yardage of earth is removed in this concrete-set anchor as compared with an earth footing.

Tower erection, as already mentioned, may be handled in two different ways. In method (*a*), where the structures are partially or wholly assembled in the prone position, and afterwards hoisted, a large crew is turned on to the work, because the basic idea of this method is speed. It is the practice in some companies to employ two totally distinct crews for assembly and erection of towers; however, it is necessary for the two to work in very close co-ordination, and it is probably best for one foreman to have charge of all tower operations. From ten to twelve towers are to be completed in one day, and sometimes as many as fifteen have been erected in good country. In one instance, in California, eight men and a sub-foreman and a team have averaged ten towers per day, each weighing 4,500 lb. With the heavier structures now commonly used as many as twelve or fifteen men would be turned over to the work of assembly and erection. Of these, four or five would be "top men," and the remainder "ground men," the former being qualified to go aloft and detach raising cables, fix crossarms, and tighten all bolts in the structure while the ground men are splicing the main posts to the foundations. If the tower is only

partially assembled, and completed when in the air, a larger proportion of top men will naturally be required, so that it may be said the average crew will consist of about fourteen men, of whom from three to six will be top men, according to the amount of assembly required after the tower is raised.

Slower progress is naturally characteristic of the unit method of construction, where the tower is built up member by member from its foundations. One large power system using towers of 12,000 lb. weight employs four men and a foreman, completing one tower a day; most other companies using the same method, however, find seven or eight men necessary, with, of course, a horse or mule team or tractor. From the nature of the work, most of the men are " top men," which is important in view of the higher rate of pay which they draw. Comparing this " unit method " with the " hoisting method " of tower erection, the following summarizes their respective features:

TABLE 51.—*Tower-erecting Crews.*

	Hoisting.	Unit.
Number of men in crew	14	7
Towers completed per day	8	1
Towers per mile	5	5
Miles completed per man-day	0.120	0.029

It is clear that the labor costs on the unit method of construction will average much higher than where the towers are assembled and hoisted, so there is good reason to use the latter method wherever the country will permit of it. Nevertheless, it is fair to mention that towers of much greater weight are erected by the " unit method," and the work is characterized by extreme thoroughness. The mechanical auxiliaries required for this method of erection are a minimum, and this often compensates for the greater labor cost.

The wire crew in the suggested plan has been divided up into two parties. This is for the reason that the cable ought to hang free for not less than forty-eight hours before it is dead-ended and clamped. It is, therefore, more economical to have

an additional crew with a winch or tractor to follow up the main party rather than have the latter work over the same section twice. The wire-stringing crew proper will require about fifteen to twenty men, a foreman, and sub-foreman. One man will be stationed at the reels to avoid kinks or twists as the wire comes off. Two will travel with the pilot line, coupling it to the cable and detaching the bridles when necessary to pass through the center of a tower, or for other reasons. They will also hoist the wire up to the crossarm men located on each tower, who will lay each cable in its proper snatchblock as it is hoisted up. There will probably be eight or ten towers in the section run out, and an equal number of linemen on the crossarms, unless conditions permit one man to handle two towers. One truck driver will operate the winch, and will be assisted by four men, who will handle the reels of pilot wire as it comes in. The foreman of the stringing crew will be located at the pulling station, being in communication by telephone with the sub-foreman, who is with the runners-out working toward the pulling station from a point from 1 to 2 miles away. Three men will make all the necessary splices, working at each reel station in turn. When the section is run out, it is pulled up to normal tension and temporarily clamped to the last tower and left for a couple of days, when the next crew will take charge. They will consist of a foreman, about four crossarm men, four groundmen and three saggers. Beginning at one end, the saggers will attach their targets, and work in the manner already described, using a level when necessary. Meantime, dead-ending is taken care of by a group of three or four crossarm men and the same number of groundmen, as well as a tractor or winch driver, with the necessary tackle. The tension will be checked by the dynamometer, as, notwithstanding that the lines were correctly tensioned one or two days before, it will usually be found that the cable has accumulated a little slack and the stress has diminished.

It must not be forgotten that a steel or copper-clad ground wire is often strung along the apex of the towers, and this op-

eration requires additional labor if progress is to be maintained. The inaccessible position of the ground wire and difficulty of straining it up make it rather more troublesome than a conductor cable.

As regards the "cleaning-up" operation, this may be thought superfluous, but it is of the utmost importance where the right of way lies through cultivated country that all temporary anchors shall be removed, as well as the *débris* of broken crates, empty drums, scrap copper and aluminum and other waste material, otherwise the goodwill of the local population towards the power company may be jeopardized and damage claims may result. A responsible man will accompany the cleaning-up crew to observe and report any irregularities in the construction work. A most important function is the recovery of tools which have been overlooked by the preceding men. Generally, a sub-foreman, a truck driver, and two laborers will form the cleaning-up party.

TABLE 52.—*Personnel of Field Crews.*

(*For construction of a double-circuit 150-kilovolt tower line.*)

Division.	Work.	Number of Men.	
		Minimum.	Maximum.
A	Distribution	4	8
B	Foundations	6	12
C	Tower erection	6	15
D	Wire-stringing	12	20
E	Wire clamping	10	16
F	Cleaning up	4	8
	Total	42	79

Equipment.—For line construction work the necessary equipment falls into two groups: (*a*) the essential tools for the work, and (*b*) machinery and apparatus which can be introduced to save labor. In class (*a*) are included (besides the conventional spades, wrenches, and other tools) post-hole augers, guy anchors, foundation templates, shear legs or gin pole, hoisting shoes,

blocks and tackle for hoisting, comealong clamps for running out cable, snatchblocks, chain and rope tackle, dynamometers, thermometers, wind gauges, and sagging targets; also the necessary clamps or hydraulic apparatus for jointing. In class (*b*) come mechanical hole diggers, jackhammer drills, mechanical tampers, underslung winches for raising towers and stringing wire, stationary winches, and tractors. Concrete mixers are sometimes used on a large job, though hand mixing will be preferable for isolated locations.

Post-hole augers are of the standardized manual type, and in reasonably good ground effect a considerable saving of time besides yielding the minimum disturbance of the surrounding soil. Although the holes bored will not be large enough to insert a ground stub and grillage for steel tower construction, they will accommodate the Malone type of concrete footing; in fact, the great merit of this type of foundation is the small disturbance offered to the soil. For setting such a footing, the post-hole auger is used in conjunction with a template consisting of a timber frame having an angle-iron guide at one corner aligned to the angle of the tower posts. When the shank of the auger rests in this guide, the hole will be drilled at the correct inclination.

The screw guy anchor is a development of the auger, the blades being wider and with a shorter pitch. Such an anchor is screwed into the ground about 6 or 7 feet deep, and the eye at the end of the shank is used for seizing a block and tackle, or for a temporary or permanent guy line. Such an anchor, in good condition, will withstand a pull of 5,000 to 7,000 lb., although for permanent construction it has the disadvantage of yielding slightly under a heavy load

The footing template forms a most useful item in the construction equipment, and although dispensed with on some tower lines of recent construction, its use is generally to be recommended to ensure accurate setting of foundation. Two-inch by 2-inch by $\frac{3}{16}$-inch steel angle is used for making up the template, except for its corner posts, which are more usually about

$4 \times 4 \times \frac{1}{4}$, and are inclined to the required angle. When the holes are dug, the stub angles are inserted and their upper ends bolted to the template. The latter is levelled up, and the holes backfilled and tamped or the concrete poured, following which the stub angles are carefully blocked up to prevent movement and the template removed to the next location. In a few instances a light wooden template has been used, but such a device is of doubtful value. Shear legs and gin poles have already been referred to in connection with tower erection. The difference between them is that the shear legs swing on the same hinge as the tower posts, and are always at right angles to the axis of the tower. The gin pole, on the other hand, is fixed and held perpendicular by guys. The latter is, of course, essential when the towers are to be built up by the unit method, and its lower end is fitted with a shoe or a hook so that it can be set up on any of the tower bracings as erection proceeds.

Hoisting shoes or hinges are used to guide the tower posts directly on to the stubs when hoisting, and to reduce friction. On many occasions, as previously mentioned, towers have been raised by attaching the lower ends of the post angles to a 6-inch pipe laid crossways on the ground and anchored to the stubs; the pipe would rotate as the tower was brought up. However, a good deal of pinching was often necessary with a heavy tower to bring the posts into the correct position, and hoisting shoes were devised to facilitate the work. The essential part of the device is a forged or cast steel bracket carrying a steel pin, which forms the hinge; the bracket rides against the ground stub, but is separately anchored so as to relieve the stub of the horizontal thrust. The shoe proper is hinged on the pin, and provides a flat plate to which the tower post can be securely bolted.

The blocks and tackle used are generally to the following specification:

> For tower hoisting: one quadruple 12-inch block and tackle reeved with ½-inch steel.

For back and side guys: one triple 8-inch block and tackle reeved with ¾-inch hemp.

In hoisting heavy towers by means of a tractor or caterpillar two sets of triple blocks are sometimes preferred, so as to keep the operation under perfect control. For temporary dead ends steel or wrought iron ground pins are used, these being about

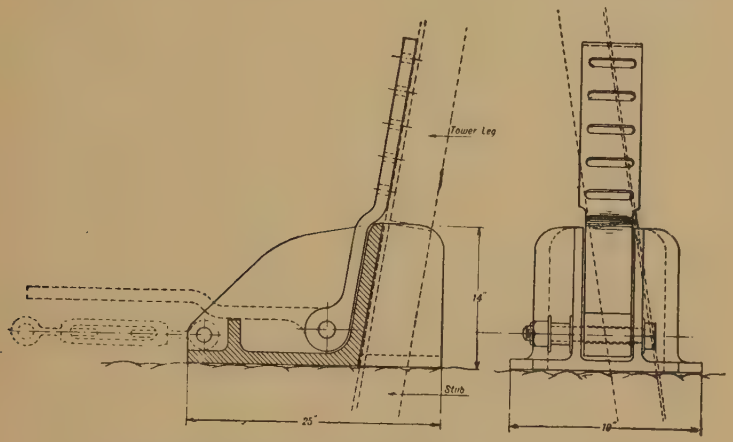

FIG. 105.—Hinged shoe for raising tower from prone position.

4 to 5 feet long and 1 ½ inches diameter. Used in combination with a chain, five of these pins are driven into the ground to within 6 inches of their top; the chain is attached to the tops, and so provides a snubbing point which will withstand 5,000 to 7,000 lb. pull in good ground.

The tools used in stringing the wire must of necessity be very carefully designed and inspected, because not only are injuries to the conductors easily caused, but such injuries are of the greatest possible significance, and may necessitate portions of the wire having to be cut out and scrapped. The comealongs, which grip the cable when straining up, are of two types, those on the wedge and on the lever principle. In either case the length of the jaws ought to be about ten times the diameter of the cable, and the jaws should be lined with the same material as the conductor, *i.e.*, soft copper or aluminum. It is sometimes

said that the comealong is attached to the end of the cable which will be trimmed off, and therefore damaging the wire is of no consequence. This is not true; a good clamp should be applied to the cable at any point whatever to pull it up without damage.

It is unfortunate that there is no commercial clamp on the market which will strain up the heavy cables in common use today, and the necessary comealongs are usually fabricated especially for the work. Some construction engineers prefer a solid bolted clamp, which will not release the wire if tension is reduced accidentally. Such a clamp is made of cast steel in two parallel halves, each with a groove. The two halves are hinged and are closed over the cable, being secured by hook bolts. Such a clamp is of particular value with aluminum-steel

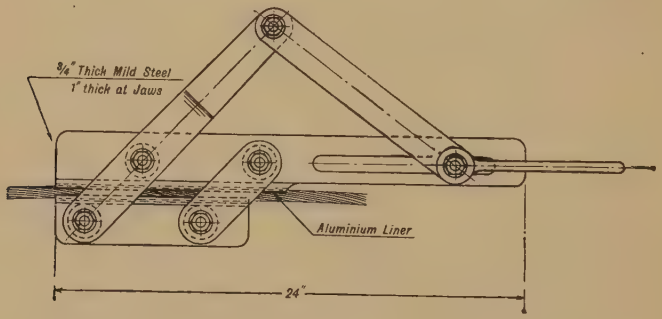

FIG. 106.—Forged steel comealong clamp on toggle principle.

cable, because the composite wires are solidly clamped together, minimizing the possibility of "dragging" the aluminum envelope.

As already mentioned, cables are pulled out over wood snatchblocks which hang by a length of chain from the crossarms. It is essential to reduce friction to the minimum not only in order to minimize the energy necessary to pull up a long section of cable, but because friction usually involves damage to the wire. A special form of block has, therefore, been devised for this work, using a lignum-vitæ sheave 7 to 12 inches diameter mounted on roller bearings housed in heavy oak cheeks.

The strap has a hinged portion on one side to enable the conductor to be laid on the sheave. These snatchblocks must be regularly inspected and lubricated, as almost the entire success of wire stringing depends upon them. In the case of a line using pin-type insulators, the block is of somewhat different form, being made to ride upon the crossarm instead of hanging below it. The same is true of installation of the ground wire, which is commonly run in a most inaccessible position at the extreme summit of the tower. For all such blocks, however, the hardwood sheave and roller bearings are retained.

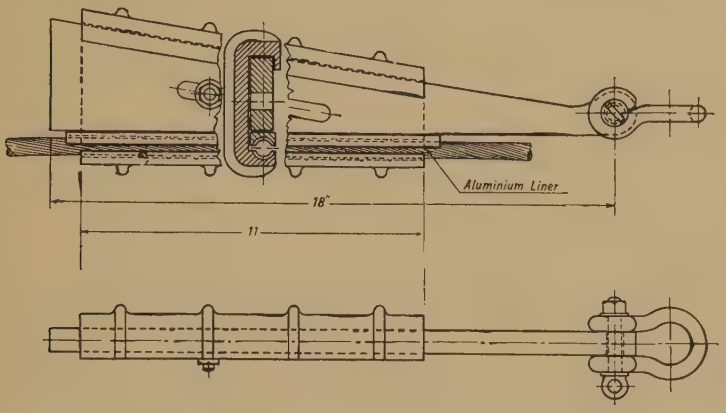

FIG. 107.—Forged steel comealong clamp on wedge principle.

Tension dynamometers used for wire stringing are of a special type, which will combine reasonable accuracy with resistance to hard wear and tear. Generally the range of stringing tension can be approximately foretold by reference to the prevailing temperature, and a dynamometer selected which will give suitable readings.

Sagging targets can best be improvised on the field, because the background will modify the scheme used. Two lengths of white pine, 2 inches × 1 inch, bolted transversely to adjacent towers at the correct height and distance offer the most simple method of sighting. The farther target should be painted white if working against a dark background, but if against the

sky, no painting is required. A small telescope is useful for spans of 800 feet and over, and can be clamped to the beam. For very long spans on steep grades a surveyor's level offers the only accurate method of sighting for sags.

The equipment for splicing in the case of simple cables consists of a pair of tongs by which the oval sleeves can be twisted, but in the case of composite conductors additional devices are necessary. In most parts of the world some form of twisted sleeve joint is standard practice for transmission wires, except where the size of cable is too large. In France and Germany, however, a good deal of use has been made of conical-seated connectors. Twisting tongs ought to be provided with handles not less than 4 or 5 feet long to secure even turning, and preferably one end should be fixed while the other is twisted; this will yield more uniform twisting with less effort, and is effected by driving a 4-foot length of 2-inch pipe into the ground and using this as a socket to hold one of the tongs. Since the oval sleeve is usually of soft copper or aluminum, it may be injured by the grips if these are not carefully designed; it is, therefore, usual to make the jaws of aluminum or hardwood with a rounded edge. Another device is necessary to hold the sleeve straight while twisting. For this purpose a pipe is used somewhat shorter than the joint; the pipe is hinged, and can be placed over the sleeve before twisting and afterwards removed.

As already mentioned, the compression type of splice is used with aluminum and composite cables, and the essential tools for the job are a small hydraulic pump and a press having a ram diameter of about 4 inches, and a total pressure of 100 tons. A variety of dies can be used, according to the size of the cable and diameter of sleeve. A certain amount of care is necessary in using the press in the field, and to maintain the leathers in good condition only oil should be employed for operation.

For conical-seated joints nothing more is required than a series of special wrenches.

Turning now to class (*b*) equipment or mechanical means of increasing manual progress, the motor vehicle has, of course,

FIG. 108.—ERECTING A DOUBLE-CIRCUIT TOWER BY THE UNIT METHOD.

FIG. 109.—HOISTING A DOUBLE-CIRCUIT TOWER ALREADY ASSEMBLED BY THE USE OF A SHEAR POLE.

[*Facing page 270.*

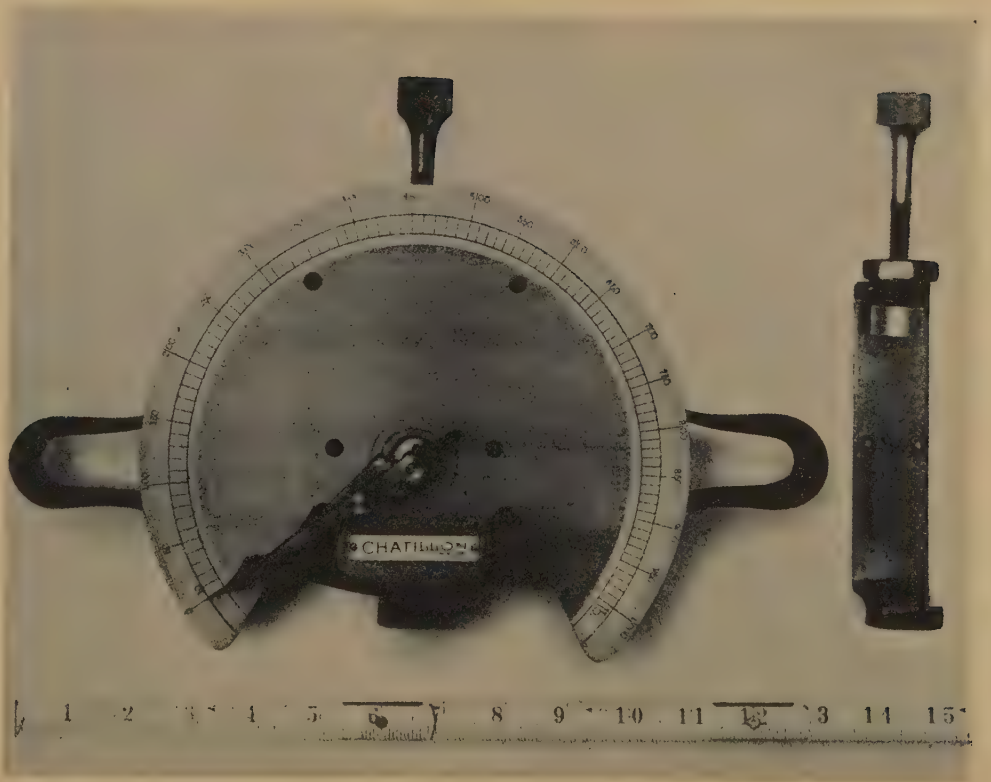

FIG. 110.—DYNAMOMETER FOR USE IN STRINGING CONDUCTOR.

[*Facing page 271.*

been of the greatest value in assisting rapid line construction. Motor trucks of a suitable type have been developed which will traverse virtually any country available for horses or mules, and such lorries or trucks can be used not merely for transporting the men and equipment to the site of the job, but also provide a means of anchoring tackle, digging holes, hoisting towers, pulling wire, and, at the same time, keeping all operations under perfect control. Where the country is too hilly for such vehicles, it is customary to substitute a pulling engine which is stationary, but the main elements can be dissembled to assist portability. In the generality of the country traversed the motor truck can be used to advantage, however, especially if shod with pneumatic tires. Such a truck is often equipped with a mechanical hole auger mounted on the tailboard, and driven by a countershaft from the gear-box. In ordinary ground a vertical hole 2 feet in diameter can be sunk vertically 8 feet deep in not more than two minutes, and the device is, of course, equally useful for pole as for tower foundations. A crane or derrick built up of two steel poles also forms part of the equipment of the vehicle, and is used for hoisting a pole bodily and lowering the butt into the hole or for handling heavy steel ground stubs.

For hoisting towers into position or stringing wire a somewhat different form of vehicle is often used, embodying an underslung winch mounted under the deck near the rear axle. This winch is also driven from the main gear-box, and the niggerhead projects from the side of the frame so as to be easily accessible. The use of a niggerhead as opposed to a winch barrel has been found to yield almost perfect control of the speed of hoisting. It is, however, important to note that only a hemp rope should be used, because steel wire is found to cut into the surface of the capstan, producing grooves which cause the rope to seize, and destroys the efficacy of the apparatus. As already indicated, transmission wires must be strung in the roughest possible mountain country, which is often unsurveyed and quite devoid of roads. Material must, in such cases, often

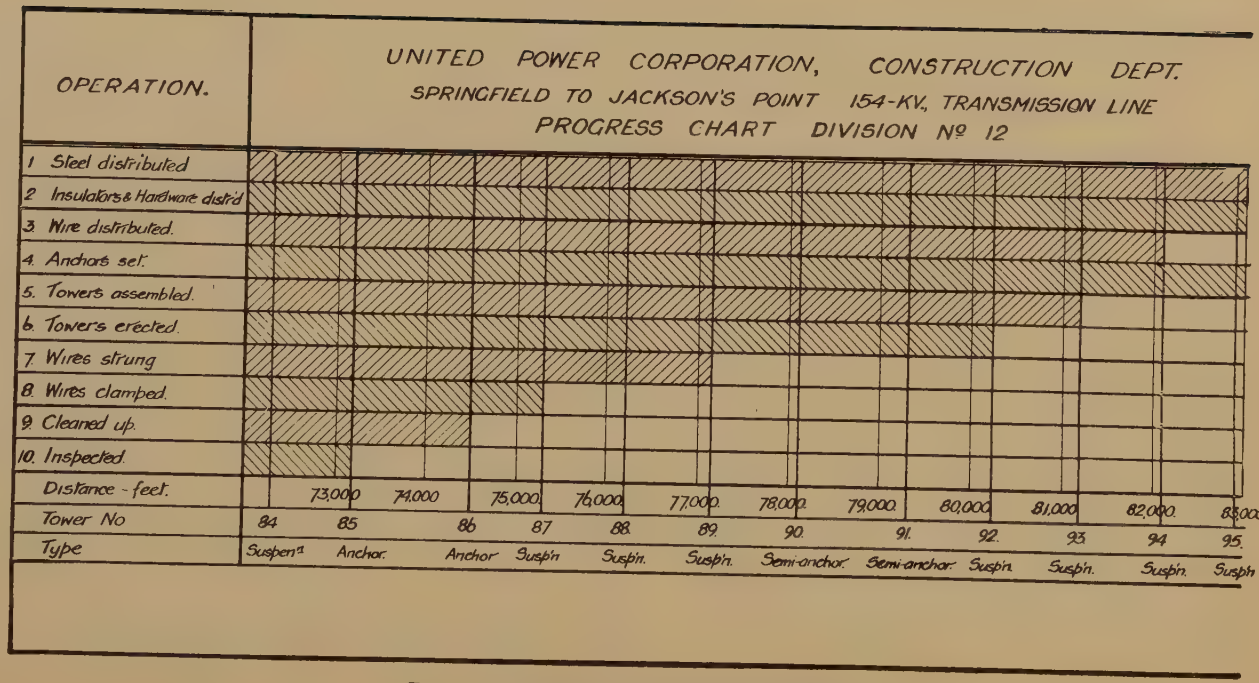

FIG. 111.—Progress chart for line construction.

be hoisted up a cableway. Wherever a reasonably favorable location offers, the pulling engine can be installed to haul out and tension up the wire. Such an engine is generally of about 6-h.p. capacity, being driven by petrol and having a worm drive with two rates of reduction, so as to give pulling speeds approximating 500 feet per minute for pulling out, and 200 feet per minute for straining up (in conjunction with a triple block and tackle). Another form of pulling engine uses two niggerheads instead of a drum, but the latter is generally preferred for wire stringing, because of the considerable length of pilot wire which must usually be reeled up. In certain cases the engine is mounted on wheels, and can be towed to any pulling location by tractor and anchored by chains to the nearest tower stubs, to ground pins, or to a patent screw guy anchor.

If no other mechanical apparatus is available, a caterpillar type of truck will be found the most useful single device. It will assist in clearing and transportation, will hoist towers, pull out wire and, with suitable tackle, strain it up, and during all this work it will operate over rocky ground or fallen logs with impunity. The Ford type of tractor is cheaper and lighter, and is useful in its own field, but the higher adhesion of the caterpillar is often necessary for heavy construction.

Setting foundations in rock calls for the use of air drills and a portable compressor driven by a petrol engine, and, owing to the cost and weight of this apparatus, it will not, of course, be employed unless indispensable. There is, however, no way of drilling rock comparable to the use of jackhammer drills. A portable compressor of the requisite type would have a capacity of 200 feet per minute at 100 lb. pressure, and be driven by a four-cylinder gas engine. The total weight of the plant would be about 3 tons, and, if available, could be used for a number of operations, such as operating pneumatic stub-hole tampers, clay scoops, etc.

Progress Reports.—High-voltage line construction is a matter involving so many details, and is generally scattered over such a wide area, that ample progress data are necessary to

the adequate control and supervision of the work. Graphic charts are of the most value, and the success of construction work is very largely dependent upon their proper use and analysis. Moreover, such diagrams periodically posted up inspire a competitive spirit among the working crews, which is an important factor in the progress of the work.

The field superintendent will cover the entire job each day,

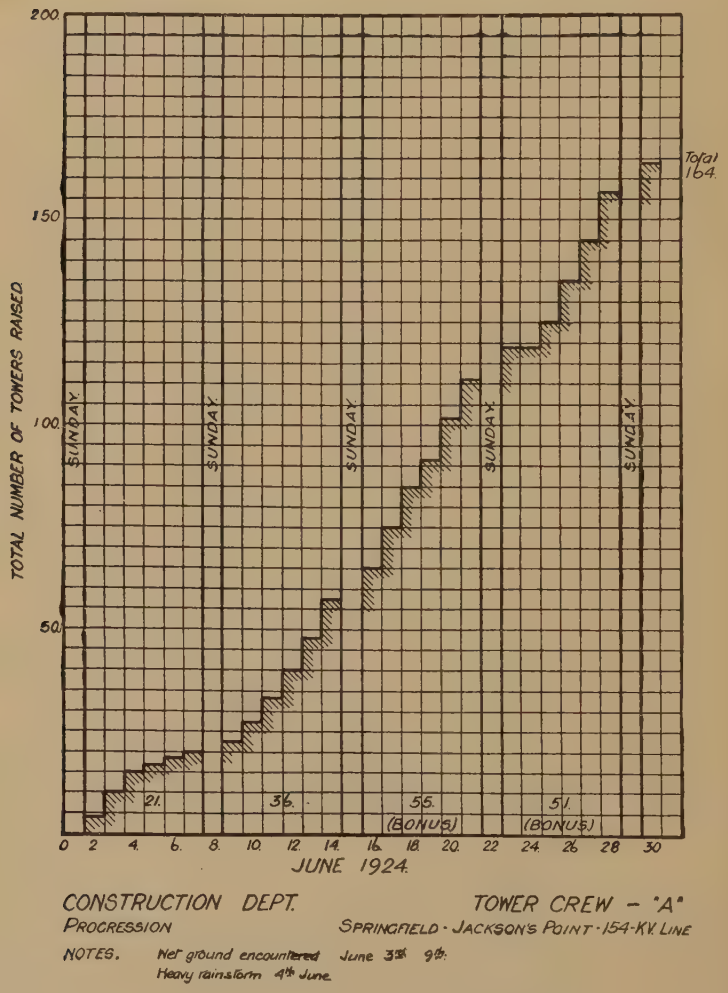

FIG. 112.—Progress chart for line construction.

receiving reports from the crew foreman covering every piece of work done up to a given hour—noon, if possible; he will survey the progress of the work, note any cause of delay, such as inadequate tools or material, bad ground or weather conditions, and his report will be transmitted to the office of the construction superintendent, where the facts will be plotted on the daily progress chart. A copy of the chart is sent to the field office daily, together with any bulletins issued and, what is by no means unimportant, a local weather forecast and barometer readings.

In most construction work it is usual to plot progress against a time base, but in line construction a base representing distance is more useful, the location of each pole or tower as well as local landmarks being indicated. On the left-hand column are indicated, in consecutive order, the various operations, usually beginning with the distribution of material, and ending with clamping wire and cleaning up. As each report is received showing the completion of the work up to a given point, the appropriate horizontal space is filled in with color and the date indicated at the end. The state of affairs at any given point along the route is shown by the corresponding ordinate on the chart. The condition at any given date is indicated by the zigzag line bearing that date.

It is best to use different colors on alternate days so as to make the daily progress more conspicuous. Absence of color, of course, indicates delay of some kind, the explanation of which should be written in by reference to the sub-foreman's report.

Another useful type of progress sheet shows the total advance made per month, plotted day by day. The chart indicates number of footings set, number of towers raised, miles of wire strung, or any other operation, and also shows immediately whether any crew has qualified for a bonus.

CHAPTER VI

ECONOMICS

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Power Development Cost.—Although the science of transmission line engineering is often associated with water-power development, it is not confined to this field, and, as a matter of fact, the most recent high-tension networks connect up a series of steam power and water-power stations. Nevertheless, it is the fact that many of the great waterfalls of the world are considerably remote from any real or potential market for power, and for this reason the maximum economy must be realized in their exploitation, not only in the capital cost of the power station, but also in that of the line.

Under modern conditions, the capital cost involved in a hydroelectric development of not less than 50,000 kilowatts is from $125 to $250 per kilowatt of plant installed, excluding all high-tension gear and transmission. The upper limit can hardly be exceeded with economy, whilst the lower limit represents with few exceptions the best which has been attained in recent years. The latest plant extensions at Niagara Falls have been installed for $100 per kilowatt, but such favorable conditions are rare. It has been estimated that approximately 5 per cent. for capital charges and 5 per cent. for operating costs are not unreasonable, making a total of $12.50 and $25.00 per kilowatt-year with a plant load factor of unity. If the load factor is taken at the more conservative figure of 0.50, the

power costs become $25.00 to $50.00 per kilowatt-year. In estimating on large power projects it is customary to eliminate the matter of load factor, and to assume that energy will be sold wholesale on a basis of maximum demand. The retailer (transmission or distribution company) will make his own rates with the consumers on an economic basis. Power factor also is subject to control, due to the wide use of the synchronous condenser sub-station. The estimates on which the great hydroelectric development at Muscle Shoals was based presume a cost of $40.00 per kilowatt-year for the primary power, and $12.50 per kilowatt-year for the secondary power at the generator terminals. By primary power is understood that which is available twenty-four hours per day throughout the year, whereas secondary power assumes certain periods of high water which can be converted into energy rather than allowed to spill over from the reservoir. The following costs were taken into account by Hugh L. Cooper & Co., the engineers concerned in the study of this project:

TABLE 53.—*Estimates for Hydroelectric Development at Muscle Shoals, Alabama.*

Total capacity (kw.)	400,000
Number of units	18
Capacity per unit	22,000
Operating head (ft.)	92
Average output, primary (kw.)	80,000
Average output, secondary (kw.)	160,000
Estimated capital cost	$5,000,000
Cost per kilowatt, installed	$125
Capital and operating charges per kilowatt	10 per cent.
Cost per kilowatt-year	$12.50

Another example of wholesale power production may probably be seen in the near future on the St. Lawrence River near Croil Island, some thirty-three miles below Lake Ontario, where a development of 750,000 kilowatts is proposed. A series of careful studies has been made, from which it is safe to assume that no technical difficulties remain in connection with this work, the one thing needful being the mutual consent of the national

bodies concerned. The investment is estimated at $200.00 per kilowatt for the entire installation, with an annual cost of power of $26.00 per kilowatt-year (on a basis of 13 per cent.). Generators for this development would ultimately be seventy-two in number, each of 12,500 kilowatts capacity, and a load factor of 80 per cent. is expected.

In a more recent study by a committee of the power possibilities of the North-Eastern United States somewhat different figures are arrived at. The cost of development of "first-grade" water power, as available at Niagara Falls and the rapids of the St. Lawrence River, is given as approximately $100.00 per kilowatt of installed plant (based on the recent installation of the Niagara Falls Power Co. referred to), "second-grade" sites of lower capacity being estimated at $160.00 per kilowatt. In the first case, capital charges amount to 13 per cent., and operation and maintenance to $2.00 per kilowatt-year. On a maximum demand basis, therefore, energy would cost approximately 15 per cent. of the investment; this wholesale cost of energy will, therefore, be $15.00 to $24.00 per kilowatt-year, an average of $19.50.

Turning to another country of extensive power development, Norway, an interesting report by S. Kloumann was submitted to the World Power Conference in 1924, dealing with the cost of power production in that country. Reviewing some thirty-seven hydraulic power sites aggregating 2,000,000 kilowatts, the costs of development were approximately as follows:

TABLE 54.—*Cost of Power Development in Norway (Kloumann).*

	Power plants in service.	Power plants projected.
Number of sites	36	37
Aggregate power (kw.)	800,000	2,000,000
Average capacity (kw.)	22,000	54,000
Cost per kilowatt developed:		
Minimum	$55.00	$20.00
Maximum	160.00	270.00
Average	73.00	78.00

It is admitted in the above report that these data comprise a

selection of the best and most profitable sites; others of greater development costs are excluded. As regards operating cost, a figure of 10 per cent. is quoted in relation to the largest plants, and 12 to 15 per cent. for those of lesser capacity. This includes all operating expenses, overhead charges, interest and amortization, and agrees closely with figures for similar large developments (both existing and projected) in America. On this basis the cost of energy at the generator terminals would be from $7.30 to $11.70, or an average of nearly $9.00 per kilowatt-year, which is distinctly lower than the equivalent American cost. Such figures probably represent the lowest rate at which wholesale energy can be purchased at the switchboard on a "maximum demand" basis, eliminating the load factor except as a matter of concern for the consumer. These conditions are represented by an electro-chemical industry, such as aluminum or carbide production, which generally operates at a load factor closely approaching unity, and is located as near as possible to the power plant so as to eliminate transmission charges. Actual rates for the supply of high-tension power to Norwegian electro-chemical works are quoted at as low as $5.00 to $8.00 per kilowatt-year; these are believed to be the lowest rates on record.

It might not be superfluous to mention in connection with hydraulic development that certain cardinal factors considerably affect the economy. Between 100 and 1,000 feet, high heads are usually much cheaper to develop than low; in general, the investment is less, on account of the lower storage required and the smaller volume of water which pipes and machinery must carry. A constant run-off is the next most desired feature, but is, of course, never met with in Nature; however, the more it approaches the ideal, the less will be the reservoir capacity, dam, and headworks required.

The hitherto most attractive sites for development have been those such as Niagara Falls, where the surplus flow of the river has eliminated the storage problem and made development cheap.

According to data recently issued by the Federal Power Commission relating to hydraulic power development in the North-Eastern United States the construction of modern high capacity power stations on sites not requiring storage (*e.g.*, Niagara or St. Lawrence Rivers) may be expected to cost $100 per kilowatt installed. The fixed charges comprising cost of money, interest, depreciation and obsolescence, insurance and taxes could be met by an annual amount of 13 per cent. and the operation and maintenance of the plant, including salaries, wages, supplies and repairs, $2.00 per kilowatt-year. The above estimates however do not attempt to represent the generality of water power sites either developed or undeveloped but simply one or two exceptional locations. In most instances a much greater outlay on storage and conduits will be necessitated though the cost of machinery may be slightly less. The following table is put forward as representing reasonably economic limits and is intended simply as a criterion in the most elementary form to show the net cost of power delivered to the high-tension substation in order that the actual cost of transmission may be arrived at. It is assumed that the primary energy is sold wholesale on a basis of maximum demand to the transmission undertaking; considerations of load factor are taken care of in the rates for distribution or retailing. In the Table, Class II represents a normally good location involving reasonable cost of construction work for dams, reservoirs and conduits. It is closely in line with a number of practical developments at the present time. I and III are respectively superior and inferior in economic merit. In a general way the three groups may be classified as follows:

Class I..... Excellent conditions
Class II..... Good conditions
Class III..... Reasonable conditions

The table relates to an installation of 50,000 to 100,000 kilowatts for continuous operation as above described with a margin of 10 per cent. for spare equipment.

TABLE 55.—*Estimated Cost of Hydroelectric Power Generation.*

	Class of development.		
	I.	II.	III.
Total capital cost per kilowatt of plant installed....	$125	$175	$225
Annual charges (both fixed and operating).....	12%	12%	12%
Cost of primary energy per kw.-year with unity load factor.....	$15	$21	$27

The mean cost of a kilowatt-year of primary energy is therefore seen to be twenty-one dollars at the power station and it becomes necessary to estimate the cost of transmitting this energy and its value at the power market. Waterfalls (especially those undeveloped) are usually remote from industrial centers and in almost every case the cost of transmission must be added to the cost of power at the source. Such transmission may involve any distance from thirty to three hundred miles but in the case of every power site there is an economic limit beyond which the energy cannot be transmitted. This radius will naturally depend not only upon the cost of energy at the source but also on the availability of fuel and the characteristics of the load at the receiving end.

The foregoing table does not include the cost of stepping up the power to the transmission voltage. Transformers and switchgear show a very marked increase in cost with increasing voltage especially above 150 kilovolts. At the same time however the appropriate capacity of the equipment is likewise increased so it is fair to say that the cost of step up substation equipment per kilowatt does not increase very rapidly with increasing voltage within the practicable range. For the present estimate it is sufficient to add $2.00 per kilowatt-year to the cost of generation to represent the operating cost of the step up station; as delivered to the line therefore the high-tension energy will cost $17.00, $23.00, and $29.00 for Class I, II, and III development respectively.

Power Transmission Cost.—No matter how economically power can be generated and sold at its source, other factors

begin to increase the cost as soon as it is necessary to carry it to the consumers' market. Every mile by which the energy must be transmitted adds its quota to the final cost of the power, and for this reason there is a distinct economical limit to the utility of a given waterfall or other power source. It is sometimes asked why such imposing potential power sources as the falls of the Zambesi River, in Africa, or the Kaieteur Fall, in British Guiana, are not utilized. The answer is simply that the distance involved in transmission is so great that the delivered energy could not compete with that already utilized from other sources. Nevertheless, conditions are changing day by day, and it is true to say that power is now being conveyed over distances which a few years ago would be thought economically impossible. The reason for this is not greater construction economy due to higher voltage or other causes, but simply the increased demand for energy. Revenue is, of course, directly proportional to the energy conveyed and sold, but capital and operating charges increase very slowly with increased line capacity. It is, therefore, natural to find that a transmission line carrying 100,000 kilowatts has a much greater economic radius than one transmitting only 50,000 kilowatts, just as the latter has the advantage over a system of 25,000 kilowatts capacity. Estimates made for the development of such great potential water powers as the St. Lawrence River generally assume the consumption of large blocks of energy, the transmission construction and costs being based upon a sufficient number of circuits, each of which carries the maximum practicable amount of energy. Under the usual modern operating conditions for a line approximately 100 miles in length this would be of the following order:

TABLE 56.—*Power Transmitted per Circuit.*

Kilovolts.	Kilovolt-amperes.
55	20,000
110	50,000
165	100,000
220	150,000

The above figures do not represent any law, but are simply illustrative of the tendencies shown by modern high-tension line practice. A good many varying factors, such as regulation, power factor, and length of line, will modify and tend to reduce these figures; it may, however, be said that the above table connotes a loss of 8 to 10 per cent., power factor maintained very nearly at unity and a length of line of 100 to 150 miles as a maximum.

Reference has been made in the course of this book to a typical high-power transmission line built with steel towers for two circuits, and operating at about 150 kilovolts and 60 cycles. The assumption is that 100,000 kva. are to be transmitted over two circuits, which is well below the physical limits of the installation. Adhering to this illustration, an estimate may be formed of the cost of transmitting energy to a distance with this equipment, and at the same time some conclusion may be arrived at in respect of the maximum economical transmission radius. Broadly, the cost of transmission is composed of three factors:

(*a*) Operation;
(*b*) Capital charges; and
(*c*) Line loss.

Operating charges cover constant patrol of the line, regular inspection and testing of insulators, and maintenance and supply of parts for renewal. The service rendered by a high-tension overhead line is a function of the vigilance with which it is watched to guard against interruptions. The operating cost is, therefore, absorbed mainly by the provision of a crew to survey the various sections of the line day by day, and to report and ameliorate any conditions hazardous to the public welfare or to safety and service. Authorities give figures which average 1 per cent. for this operating cost, the amount being, strictly speaking, independent of the power transmitted over the line. For a double-circuit transmission of the type under review the capital cost would average $16,000 per mile, and the annual cost

of operation and maintenance as above described would be $160 per mile.

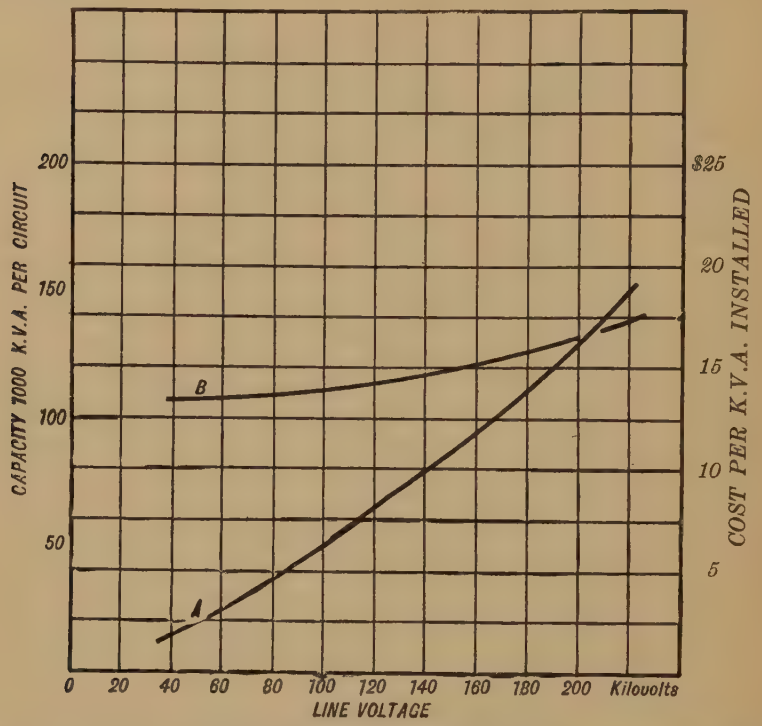


FIG. 113.—Curve A: Appropriate maximum capacity for high-tension transformer stations. B: Unit cost of high-tension transformer stations.

But the foregoing does not exhaust the factors of operating cost, and under this heading are also included 2 per cent. for depreciation and obsolescence as well as 1 per cent. for taxes and insurance. The total operation cost, therefore, becomes 4 per cent. of the entire cost of the line.

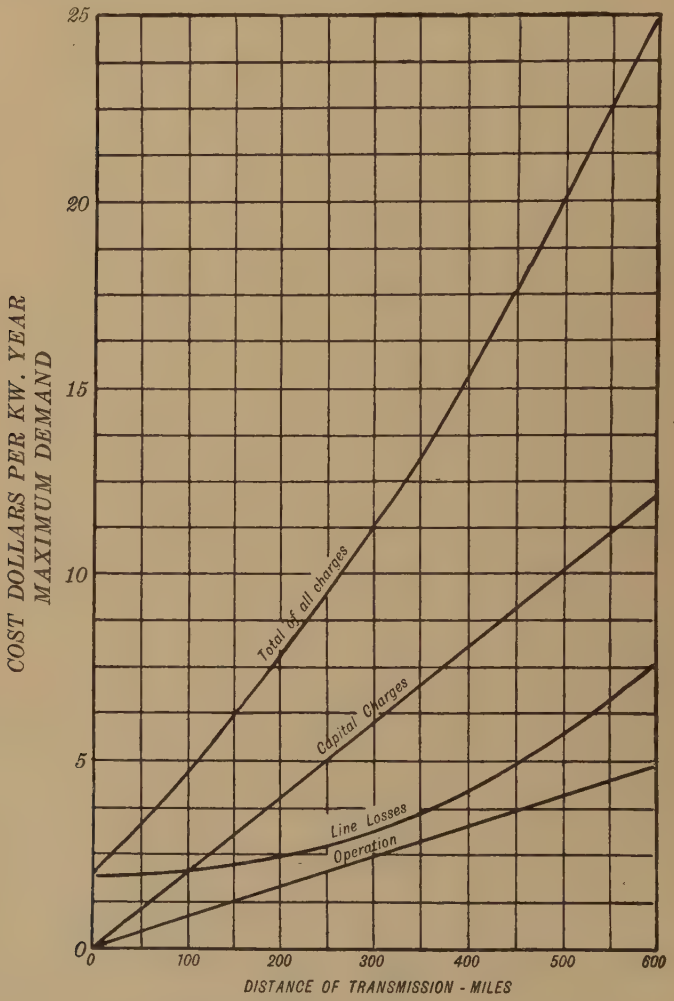
In the capital or fixed charges must be considered not only the net return which the investment justifies, but also an allowance for profits. So many estimates omit this allowance that it is justifiable to draw attention to it. Whilst under construction it is customary to charge 7 or 8 per cent. against the investment already sunk in the undertaking as the usual "interest

during construction," but when the transmission system is a going concern it is natural to expect it to do more than merely pay for the sheer cost of the money which has been put into it. A figure of 10 per cent. is, therefore, charged against the capital investment to represent interest and profit, as well as such items as discounts to banks, underwriting stock issues, and the like.

Energy losses in the line are charged at cost price as between the generating and the transmission undertakings. This should be compounded with the cost of transmitting the lost energy half the length of the line, but the present estimate is intended to be only of the most elementary character, and this has been neglected. The maximum load factor of unity has also been assumed corresponding to the maximum value of total loss. A study of transmission line operation would, of course, have to take into account the most probable load factor, whether 70, 60, or as low as 50 per cent., the latter naturally carrying double the overhead charges per kilowatt-year. In estimates leading to the sale of bulk power, however, it is assumed that rates will be fixed on a maximum demand basis; the tendency is, therefore, to attract industries which can maintain their demand twenty-four hours per day the year round, thus securing the advantage of wholesale rates. The tendency with modern large power systems entailing widespread transmission is distinctly toward the raising of the load factor.

A fair cost for electrical energy as generated in large plants and delivered to the high-tension line has already been arrived at in the vicinity of $23.00 per kilowatt-year. The curves (Fig. 114) show the increment which must be added to this amount for the cost of transmission distances up to 600 miles. If the energy could be carried this entire distance, its cost would be doubled, and on a maximum demand basis it would sell at $48.00 per kilowatt-year at the receiving station. It is prudent to mention "if the energy could be carried" that long distance, because limitations of an electrical character begin to be experienced at about 400 miles, and for longer distances at

60 cycles become not only embarrassing, but prohibitive. It is not merely that the energy losses become of increasingly greater moment as the line spreads out, but that the capacitance of the line increases to the extent that it is impossible for the generating plant to supply the charging current.



Capital charges and profit..... 10%
Losses per KVA.....$25.00
Operation, maintenance, depreciation..... 4%

FIG. 114.—Annual charges on a long 150-kilovolt transmission line.

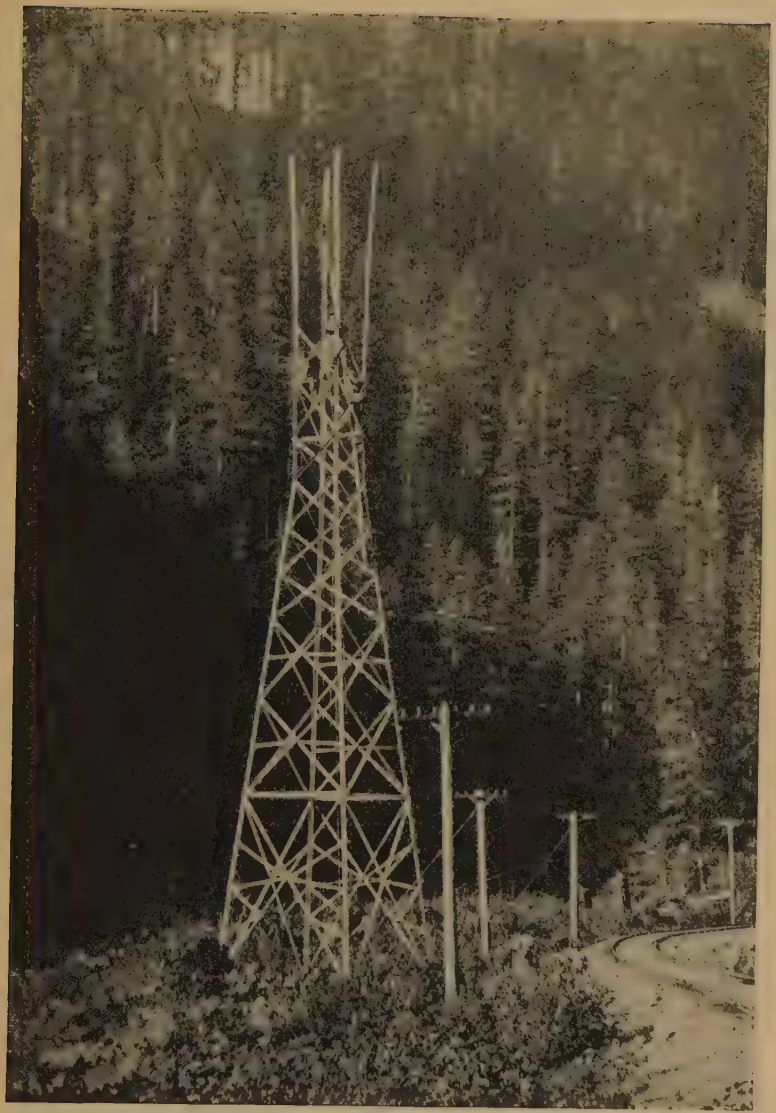


FIG. 115.—COMPLETING ERECTION OF A TOWER BY THE UNIT METHOD IN MOUNTAIN COUNTRY.

[*Facing page 286.*

FIG. 116.—TRANSMISSION LINE RIGHT-OF-WAY AFTER CLEARING IN MOUNTAINOUS COUNTRY.

[*Facing page 287.*

As already noted from Fig. 114, the energy increases in cost in the present illustration from $23.00 per kilowatt-year at the high-tension bus of the power house to $48.00 per kilowatt-year at the terminal station of the 600-mile transmission line. Further charges will be involved in the overhead and operating costs of the receiving station with its transformers, switchgear and probably synchronous converters also. The present illustrates an extreme case but it is instructive as an example of the maximum economic transmission radius. There are very few, if any, industrial areas in the United States where twenty-four-hour electrical energy in bulk could be sold for $48.00 per kilowatt-year, consequently there is little if any incentive to develop isolated hydroelectric power plants 500 to 600 miles away from the power market. A 250-mile radius is evidently within the practical range in the present instance, as it leads to a cost of high-tension energy, at the receiving station, of approximately $33.00 per kilowatt-year under the above conditions.

The foregoing summary has dealt in a general way with the increased cost of energy in relation to the distance from the power station, and has assumed a specific type of transmission line of certain characteristics, and costing $16,000 per mile to install. It will, however, be more instructive to analyze the various individual costs of the different elements of the line and to review in particular those items which may be modified in the interest of economy.

Such economies as may be effected in line construction are of the greatest importance in reducing the cost of energy, and it will be interesting to summarize the chief items of cost relating to recent construction of the most substantial character.

For estimating purposes it is convenient to divide the costs of a transmission line into four headings, viz.: (1) Right-of-Way, (2) Material, (3) Labor, and (4) Other Charges.

Right-of-way.—This is one of the most difficult questions with which the engineer has to deal, and the difficulty is more pronounced as the country is more settled and cultivated. The

cost of a right-of-way may vary from a few dollars a year per tower for the privilege of access during operation to a matter of $2,500 to $5,000 or more per mile for direct purchase of the narrow strip required for the line. Both these extreme figures have been met with in actual practice. In some instances of lines recently constructed direct purchase has been preferred; one power company, in building a line to operate at 132 kilovolts, secured a right-of-way 100 feet wide, thus allowing additional space for a further line. The cost was approximately $3,000 per mile, or probably 15 per cent. of the entire cost of the line completed. In this case, the initial capacity being about 100,000 kilowatts, and the ultimate amount twice as much, the cost of right-of-way was readily absorbed. Still more recent official estimates made in connection with a power survey of the North-Eastern United States employ a figure of $5,000 per mile for a double-circuit transmission. For lines of smaller capacity and necessarily lower capitalization such a cost will be inadmissible, and easements would have to be acquired from the property owners along the routes. Once the construction period is over, the inconvenience suffered by the freeholder is very slight. The wide base tower offers every opportunity for a plough or harrow to pass between the foundations, and crops are regularly being raised between the posts on ground for which the farmer is actually receiving rent. One instance occurs in Canada, where a high-tension line passes through an orchard, and a peach tree is growing and yielding fruit in the middle of the tower foundation. In most parts of Japan where rice is cultivated the crops are raised within the tower base, without regard to the structure at all. Patrolling is usually performed from a nearby bridle-way or footpath, and leads to no interference with crops.

An important factor to be considered is that in many cases of long transmission lines only a portion is routed over cultivated country. Most hydroelectric developments are naturally located in the mountains, in addition to which the line will probably traverse many miles of virgin country in the foothills before

reaching cultivated areas. This is found to be generally true of construction in the Western United States, in Canada, India, Australia, and Japan. Quite naturally, therefore, the average cost of the right-of-way will be reduced in proportion to the percentage of the total distance which is built across undeveloped land. The high figures quoted above may, therefore, be taken as representing only the most costly portion of the route.

In many parts of the world a public utility body has a legal right of " eminent domain," by which they can compel the surrender of the required property at a fair compensation. Where such legislation exists, it is seldom necessary to enforce it, but it affords a healthy corrective to the type of property owner who, regardless of the commonwealth, refuses to sell at any price. The development of high-tension transmission is following parallel lines to that of the railway during the years 1830 to 1850, and similar obstacles to progress are just as apparent.

Cost of clearing is sometimes itemized as a construction cost, but it should be associated with the right-of-way so that all construction work is performed upon a cleared route. Three double-circuit lines recently built in moderately-timbered country show clearing costs of $302, $381, and $504 per mile. A figure of $250 per mile is often accepted in estimates covering normal country, and in a long route conditions will usually average down. Where the right-of-way is purchased, the sale of timber may be set against the cost of clearing and leave a credit balance.

Material.—The cost of material probably amounts to 70 or 80 per cent. of the entire cost of the line (excluding right-of-way), and this affords the main incentive for careful design, which will reduce to a minimum the amount of steel, copper, aluminum, and porcelain required. Since construction and engineering amount to only 20 to 30 per cent. of the total, far less economic improvement is possible. Chief among the material used is the *conductor*. The relative price level of copper or aluminum wire and composite cables is constantly varying, but

in general it will be found that aluminum is somewhat the cheaper metal to use, even when reinforced with a steel core as already described. The higher stringing tension possible with this class of conductor makes feasible a certain contingent economy, due to the wider tower spacing; consequently fewer insulators, less insulator depreciation, tower construction costs, and wayleave easements, as well as probably less structural steel for supports. At the time of writing, stranded copper cable is quoted at 16c per lb., and aluminum at about 30c. For a line having equal loss the ohmic resistances must be equal, on which basis 1 lb. of aluminum wire is equivalent to 2 lb. of copper. In effect, therefore, aluminum shows an economy of 12 per cent. under the above conditions. Since the markets change from day to day, it is necessary to determine how much the proportion will be at any given time.

For voltages of more than 150 kilovolts it is usually the disruptive corona voltage which sets a limit on the design; in other words, if the conductor were selected for a given per cent. energy loss, it would be so small that serious corona discharge would occur. In such a case the minimum diameter is set. Now the weight of an aluminum conductor of the same diameter is only 33 per cent. that of copper, so that with the above figures the light metal would be nearly 50 per cent. more economical than copper. Steel reinforcement will add a little to the cost.

Kelvin's law of economy applies to the selection of all conductors where all the factors are included in the calculation. For instance, the heavier wires will need more substantial supports, and lead to higher construction costs; on the other hand, wires of very small section will call for much higher poles or towers and wider crossarms. Full account must be taken of the probable increase in load, and in general a conductor is selected large enough to take care of an appreciably greater load than the initial one, with probably not more than 10 or 12 per cent. line loss. However, the loss is, in high-tension lines, second to the regulation, which affords the real basis upon which the line

is calculated. The electrical engineer determines the size of wire which, for the particular length of line load and frequency, will give the most favorable characteristics. Calculation of the annual loss in the line depends upon a determination of the square root of the mean of the squares of the varying loads throughout the year, and the number of assumptions necessary renders the results almost conjectural.

It has been already indicated that the comparison between two forms of conductor is not necessarily made on the basis of equal resistance, but of equivalent reactance and corona characteristics. For this reason it will be found that the diameter of the cable is more significant than its area, and on the basis of a given diameter very considerable economies can be realized by the use of aluminum with reinforcement.

A ground wire is often strung along the apex of the towers; such a wire is commonly of galvanized Siemens-Marten steel, having seven strands and a finished diameter of $\frac{3}{8}$, $\frac{7}{16}$, or $\frac{1}{2}$ inch. The cost may be estimated at 5c to 7c per lb. Since, however, the deterioration of galvanized steel wire is somewhat more rapid than the other elements of the line, it is becoming more usual to employ copper-clad cable of the above size, at a cost almost the same as copper.

Insulators are the next important item in the cost sheet. Present (1926) prices for modern pin type and suspension type units are shown in the curves (Figs. 117, 118); the latter are subject to some modification according to local conditions, which may warrant one or two units more or less per string. Cost of insulators per mile of line is, of course, an inverse function of the span length.

Clamps for fastening the conductor wire are associated with the insulators, and will probably cost from $2.00 to $3.50 per insulator for suspension, and $8.00 to $12.00 for dead-end points.

Supports are covered by the market price of small structural steel shapes cut to length, punched, and galvanized, which varies between 5c and 8c per lb. In some countries, where it is cus-

tomary to paint the towers, ordinary black sections will be requisitioned from the mill, thus saving at least 1c per lb. The galvanized tower is, however, more nearly standard. Wood poles are, within the limits of their use, considerably cheaper than steel, but with few exceptions are confined in their use to lines of less than 66 kilovolts or to construction of secondary character. In estimating for towers, full allowance must be made for footings, extensions, transposition structures, and all special construction necessitated by local conditions, which increase the total steel very considerably over that estimated for an " average " tower line Allowance must also be made for bolts, which also form an appreciable item.

It is customary for structural steel engineers to quote a price " per tower " rather than " per pound," so as to take account of the variations in design. Two towers of the same weight may have widely different costs, and the number of bolts required forms one factor in such a case. While the price of structural steel is a reasonably uniform figure at any time, the cost of wood poles is subject to too many variables to generalize upon it. As already mentioned, accessibility of good timber is, in most parts of the world, the chief factor in its use, and where it is scarce the tendency will be toward the use of steel. Similarly, the cost of concrete poles is affected by the location of the transmission line, and in view of the very great weight of these supports, freight costs will limit their use.

Other material for line construction includes Portland cement, stone, and sand for foundations, which must be estimated according to local conditions.

Labor.—As already indicated, the costs of labor for transmission line construction are generally of the order of one quarter the entire cost of material. In America, where the highest rates are paid, the construction crews are the smallest, because of the employment of mechanical aids to construction and the high efficiency of the individual workers. Where common labor is not of such a high order, for example, as in India or the Far East, the crews are necessarily much larger, but the

progress is generally less. Therefore, in spite of the great diversity of labor rates, there is somewhat of a tendency for the range of labor costs per mile of line to narrow down to reasonable limits.

For substantial modern steel tower construction in America, using double-circuit lines, the following labor costs are illustrated:

TABLE 57.—*Costs of Assembling and Erecting Double-Circuit Towers for* 110 *Kv. Costs in Dollars per Tower.*

System.	Weight of tower.	Cost of steel.	Excavation, setting stubs, backfill.	Assembling and erecting.	Total cost erected.	Material. Per cent.	Labor. Per cent.
A	4,800 lb.	192.00	28.00	15.00	235.00	81.5	18.5
B	3,100 "	112.60	13.50	7.00	133.10	81.3	18.7
C	5,554 "	194.00	148.00		342.00	57.0	43.0
D	3,900 "	136.50	25.00	14.75	176.25	77.5	22.5
E	4,800 "	347.00	120.00	5.70	472.70	73.5	26.5
F	6,111 "	280.00	135.00	54.50	469.50	60	40

NOTE: Systems A, B, and C are located in the Southern States, D and E in Canada and F in the Middle West; C, E and F use partly concrete foundations, others ground stub and grillage. All structures were assembled prone and hoisted by a winch or tractor.

The foregoing costs relate to the highly-paid labor prevalent in the eastern part of the country, rates being from $6.00 to $14.00 per day, and the figures include all distribution of material as well as excavation, assembling, stringing, and clearing up. Whilst only three examples are quoted, they are based on work recently done, and are reasonably representative.

Some individual costs for detailed construction in the United States and Canada are appended; they have been published by the engineers of the respective systems during the past ten years, and have been corrected for the prevailing rate of exchange:

TABLE 58.—*Labor Costs for Transmission Line Construction.*

System.	Clearing.	Construction.	Total labor cost per mile.
A.....	$302	$1,107	$1,409
B.....	501	1,047	1,548
C.....	381	1,493	1,874

Wire stringing is next in order after tower erection, and the labor cost naturally depends very materially upon the weight of cable being strung. The following figures are reported for the Turner's Falls Power Co., in Massachusetts, and represent double-circuit 110-kilovolt construction using six copper wires substantially all of 3/0 B & S or 168,000 cir. mils area. Three distinct and different lines were built at different times.

TABLE 59.—*Cost of Conductors and Stringing.*

System.	Cost per mile. Dollars.				
	Wire.	Stringing.	Total.	Material. %.	Labor. %.
A.....	3,014	364	3,378	89.2	10.8
B.....	2,652	374	3,026	85.9	14.1
C.....	3,570	494	4,064	87.8	12.2

In comparing costs of wire stringing on different systems very wide variation will be found due to varying sizes of conductor, character of ground and other factors. The following table gives further labor cost data for a number of widely different conditions. It will be noted that the heavy conductors cost a considerable amount to handle because of their weight and this is the reason why mechanical handling methods are now being so extensively adopted in the field.

TABLE 60.—*Cost of Stringing Wire (Per Mile).*

System.	Supports.	Circuits.	Ground wire.	Conductor.		Labor cost per mile.
				Material.	Size, cm.	
D	Poles	1	—	Aluminum-steel	168,000	$ 130
E	"	1		Copper	66,400	204
F	"	1		"	133,000	467*
G	"	1		"	133,000	510*
H	"	1		"	133,000	525*
J	Steel Poles	1		"	83,700	110
K	" "	2		"	106,000	141
L	Tower	2		"	168,000	242
M	"	2		"	212,000	660
N				"	400,000	1,090

* Figure includes hauling.

Charges sometimes associated with labor are general expense and indirect expense. The former covers insurance and taxation, deficit on commissariat, and similar items, while the latter covers the building of roads or paths having a permanent value. These are treated separately under "Other Charges."

TABLE 61.—*Transmission Line Construction Cost Sheet.*

(A) RIGHT-OF-WAY.

(1) *Land.*	(2) *Surveys.*	(3) *Preparation.*
(11) Freehold.	(21) Reconnaissance.	(31) Cutting timber.
(12) Easements.	(22) Final survey.	(32) Grading.
(13) Legal.	(23) Tower location.	

Total Right-of-Way.....

(B) CONSTRUCTION.

(1) *Labor.*	(2) *Material.*
(11) Distribution.	(21) Towers.
(12) Excavation.	(22) Conductors.
(13) Setting towers.	(23) Ground wire.
(14) String-wire.	(24) Insulators.
(15) Cleaning up.	(25) Hardware.
(16) Special work.	(26) Cement.
	(27) Other material.

Total Construction.....

(C) OVERHEAD.

(1) *Engineering.*	(2) *Contingencies.*	(3) *Interest.*	(4) *Other Charges.*
(11) Preliminary.	(21) Lost time.		(41) Camp establishment.
(12) Inspection.	(22) Material damaged in field.		(42) Cookhouse.
(13) Office work.			(43) Insurance.
(14) Field supervision.	(23) Material received defective.		(44) Plant maintenance.
			(45) Field office.
			(46) Taxes.

Total Overhead.....

Whilst steel tower construction is coming to be regarded as standard, it would be unwise to neglect the very appreciable extent to which wood pole lines are being built, even where the voltage amounts to as high as 165 kilovolts. Under certain

conditions the cost and deliveries of steel become prohibitive, and a substantial form of wood pole line must be built if the service is to be rendered. In the following tables are given the actual construction costs of a power transmission line for 110 kilovolts in the South. The line is built with an "H" pole arrangement, using chestnut poles 50 feet long having cross-arms of creosoted yellow pine 6 × 8 inches, and a standard span of 400 feet. The poles were set with 7 feet 6 inches in the ground.

TABLE 62.—*Construction Costs per Mile for Single-Circuit Wood Pole Line. 110-Kilovolt.*

	Quantity.	Unit price.	Total.
MATERIAL:			
Poles	18	$24.50	$441.00
Crossarms	11	11.00	121.00
Hardware	1,800 lb.	.12	216.00
Insulators	260	2.50	650.00
Wire (1/0 Aluminum)	2,300 lb.	.25	575.00
Splicing material	—	—	6.00
Ground wire	3,600 lb.	.08	288.00
Miscellaneous	—	—	50.00
TOTAL MATERIAL			2,347.00
LABOR:			
Distribution	—	—	189.00
Excavation	18	11.00	198.00
Assembling	9	12.50	112.50
Erecting poles	18	6.40	116.00
Miscellaneous (pole setting)	—	—	62.50
Distributing wire	—	—	12.00
Stringing conductor	—	—	105.00
Stringing ground wire	—	—	85.00
Miscellaneous (stringing)	—	—	15.00
TOTAL LABOR			895.00
TOTAL CONSTRUCTION COST			$3,242.00

Extra to the above costs are engineering, right-of-way, supervision, and all overhead charges, which will probably total up to 50 per cent. of the above figure, making the entire capital cost from $4,500 to $5,000 per mile.

Other pole lines built in the Western United States, also for 110 kilovolts, but employing single cedar poles with framed

steel channel crossarms, show remarkable similarity to the above costs. It may be said that $3,500 represents the construction costs of a high-class pole line for 110 kilovolts, while $5,000 is a fair amount for the entire capital cost (single-circuit in each instance).

Other Costs.—In addition to material and labor, a number of charges are incurred under the headings of Engineering, Surveys, Contingencies, Interest during Construction, and Overhead. Cost of *Engineering* (including supervision) is often estimated at 3 per cent. of the total cost of the entire job. For a typical high-tension line costing $15,000 to $20,000 per mile the labor charges would be of the order of $3,000 to $4,000, and engineering and supervision $450 to $600 per mile, which is a reasonably low figure. *Surveys* are also sometimes included as a labor item, but should more properly be considered separately. Considerable diversity is to be expected in this item, but, failing more particular information, limits of $150 to $300 per mile may be assigned. Since every tower location must be levelled and staked, the survey work will be a little cheaper as the spans are increased. Generally, however, the character of country will be the most significant factor in the cost of survey, but, as already indicated, on a long route this has a tendency to average down. Contingencies are sometimes estimated at 10 per cent. of entire cost of construction and material, although some estimates use a figure as low as 5 per cent.

There is no reason, however, in a properly engineered job, for the last figure to be overstepped. Sufficient data are available for the work to be thoroughly planned before construction is begun, and with few exceptions all conditions may be foreseen and allowed for. A tower may be damaged by the wind or possibly dropped during erection; a crossarm may be bent by the stringing crew when straining up; wet or rocky ground may impede progress. Nevertheless, all these possibilities should be generously covered by a 5 per cent. contingent allowance.

Interest charges during construction are, of course, based

upon the money rate prevailing, usually 7 or 8 per cent. in America, for construction purposes, on the total investment concerned and upon the time taken for construction after the money is raised, but before it becomes productive. The cost of the job gradually increases from the initial date as further deliveries of material are received and further labor charges incurred, until, when the last piece of work is done, the entire undertaking is capitalized. During construction, therefore, an average of one half the total investment will be subject to interest for the whole period. The prudent engineer will, as far as possible, reserve the installation of expensive plant and machinery until towards the end of construction; in other words, do the cheapest part of the work first so long as the total progress is not jeopardized. Since interest charges can be reduced by decreasing the time of construction, it is often legitimate to incur increased costs to secure greater speed. If a construction crew can accomplish a basic average progress of ten or fifteen miles per month, then to build a 200-mile line in one season, between March and October, will necessitate at least two crews in the field; but this construction time can be nearly halved with four crews working. Overhead will, however, be increased by reason of extra trucks, winches, tools of all kinds, and camps necessary. This increased overhead will call for an enhanced investment and interest charge, so that the various factors involved must be carefully balanced when determining the most economical construction speed.

Further charges of varying amounts have to be met under the heading of *Overhead* expense in respect of the establishment and maintenance of camps, mess rooms, and other facilities for the men. In some instances it is customary to equip a semi-permanent camp for each section of the line, if the route is long, at which the crews assemble to sleep every night; in other cases, where the country is more populated, they are billeted on nearby farmhouses, and in contiguity with large towns there is generally no special arrangement necessary. It is obvious that

the costs under this item will show considerable variation according to the type of country traversed.

Estimates.—In the latter part of the chapter on Design a series of mechanical constants are arrived at relating to a modern high-tension transmission line operating at 150 kilovolts, and transmitting 100,000 kilowatts over two circuits. The study includes both aluminum-steel and copper conductors, and a maximum tension is used in the wire of 40 per cent. the ultimate strength of the cable. It will be interesting to carry this brief study farther by estimating the various costs of material, labor, and overhead. At the same time, it is hardly necessary to mention that any estimate is particular, and not general. The figures used are representative of construction which has been effected in Canada, Australia, and the United States during the years 1923–1925, in undulating country with a relatively small percentage of difficult ground, such as hard rock or swamp. The object of the presentation, however, is rather to outline a method of estimating than to derive any result of general economic value. Since a comparison is presented between two different types of conductor, it is especially desired to study such items as vary with the conductor material used.

Considering first the *Right-of-Way* for the double-circuit line, an average of $5,000 per mile has been assumed, this amount to include all surveys and clearing, and covering a strip of territory 150 feet in width. On lines of recent construction right-of-way has been secured for not more than 25 per cent. the above amount, but a conservative figure has been adopted because of the great variations in this item.

Material can, of course, be estimated with fair accuracy allowing for variation in the markets, freight haul and local conditions. For the line under consideration copper conductors of the requisite area (255,000 cir. mils.) will weigh 4,130 lb. per mile and six conductors would therefore amount to 24,780 lb. approximately. An allowance of one per cent. will be added to this to cover splicing material, tie wire and sleeves, making

25,028 lb. at a representative estimating price of 16 cents per lb., giving as the total cost of conductors $4,004.

If, for comparison, aluminum-steel conductors be considered, it will be necessary to ascertain the composite price of the conductor. For 415,000 cir. mils standard thirty-seven stranding as in the present example the weight of the conductor will be approximately divided between sixty per cent. aluminum and forty per cent. steel. Estimating twenty-nine cents per lb. for the aluminum and six cents for steel, the cost of the composite cable comes out at 20 cents per lb. The weight of the single conductor is 3,470 lb. per mile and of six wires 20,820 lb. An allowance of one and a half per cent. will be necessary for splicing material, making a total weight of 21,130 lb. at 20 cents or a total cost of $4,226.

On the actual cost of wire therefore copper shows an advantage of 5.3 per cent.

The cost of insulators is a function of the number of towers per mile, and comparing the sag templates of the two conductors with the undulating profile, it is found that for copper wire there will be an average of 7.3 towers per mile (720-foot span), and for the aluminum-steel cable with the same clearances 5.4 towers per mile (980-foot span). Using six high-strength insulators on each suspension tower, allowance must be made for extra strings at semi-anchor and transposition towers, besides the necessary twin yokes for anchor points. An increment of 15 per cent. to the units required at all suspension points will give the necessary total. For the copper wire installation there will be forty-four strings per mile plus 15 per cent., or fifty-one strings at $32.50, a total of $1,655.

In the case of the line strung with aluminum wire there will be thirty-two plus 15 per cent., thirty-seven insulators per mile at the same unit price amounting to approximately $1,200.

The number of clamps and fittings required is generally a function of the number of insulators, but there is a tendency for hardware of this kind to cost more for aluminum-steel cable, not only because of its greater diameter, but also on account of

the greater complication of the clamps. Making full allowance for the relative numbers and prices, the total cost of hardware and clamps per mile for the copper conductors averages $80 and for the aluminum line $135.

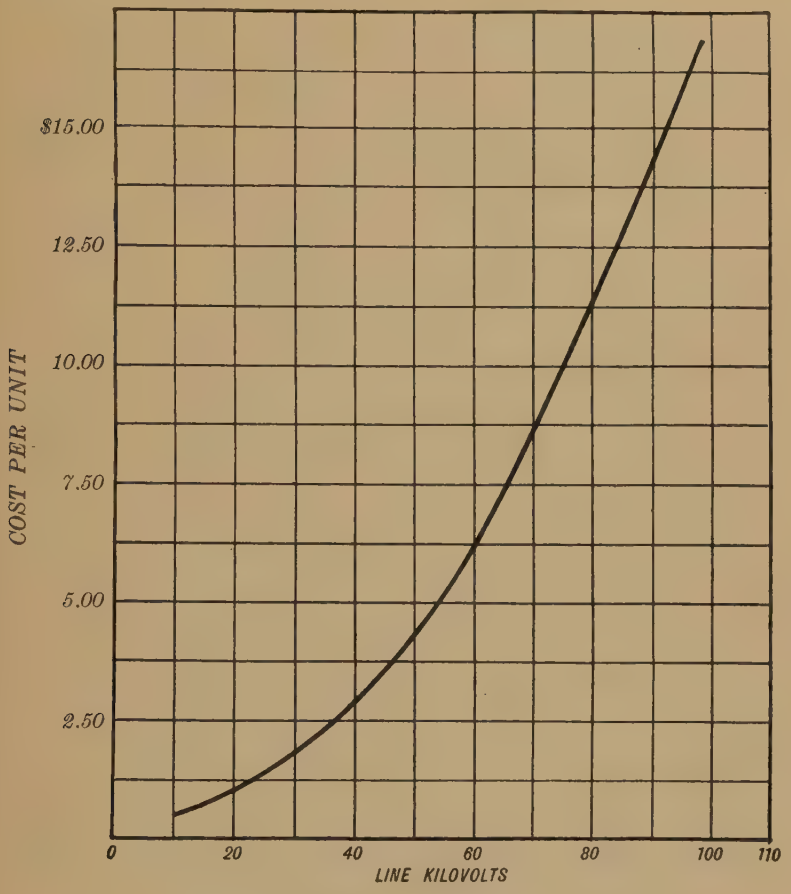


FIG. 117.—Estimating cost of pin-type insulators.

These figures include the clamps used in jumper connections.

The structural steel *Towers* form one of the most significant items in line construction. At the time of writing (February, 1926) the price of galvanized steel sections of the requisite size and shape (including the necessary allowance for bolts)

is from 6c to 8c per lb. By laying out the designs the individual weights of the towers for the respective test loads in Chapter IV. are found to be as follows:

TABLE 63.—*Weight of Steel Towers for the 150-kilovolt Transmission Line.*

Conductors.	Copper.	Aluminum-Steel.
	lb.	lb.
Suspension Tower	5,800	7,850
Semi-anchor Tower	7,550	11,600
Anchor Tower	10,200	17,100

In a distance of 100 miles on the copper line there will be 734 towers, of which only 5 per cent. will vary from the suspension type, there being thirteen anchor and twenty-six semi-anchor towers. The total weight of tower steel, therefore, averages 47,585 lb. per mile, with an allowance for extension angles and other excess steel of 5 per cent., making 49,200 lb. At a price of 7c per lb. this item becomes $3,442

In the case of the line strung with aluminum-steel conductors, as already seen, the average span is longer, and the total number of towers used on the 100-mile route is 540, of which ten will be of the anchor type and twenty will be semi-anchor. In this case, reducing to a one-mile section, the total weight of tower steel becomes 44,030 lb., and with the allowances for extras, 46,300 lb. At the unit price above quoted, therefore, the cost of the steel becomes $3,241.

It is of interest to note that the individual towers for the aluminum-steel conductors are appreciably heavier than those for copper, but owing to the smaller number required to conform to the profile there is actually a net economy of 5.8 per cent. in favor of the reinforced conductor. It will be found in practice that this economy may be much greater if the country is very mountainous and the profile irregular, whereas in level country the saving may entirely disappear.

Other Material may be said to include cement for the anchor tower foundations, reinforcing rods, rock anchors, guy wire, and small supplies, and would probably be met by an allowance of $75 per mile.

Turning to the important item of Labor, it will be found that the cost of most operations, such as distributing material, setting foundations, assembling steel, and stringing wire, is a function of the number of towers. The greater distance traversed in the case of the longer spans is not found to have any perceptible influence, nor has the difference between the weight

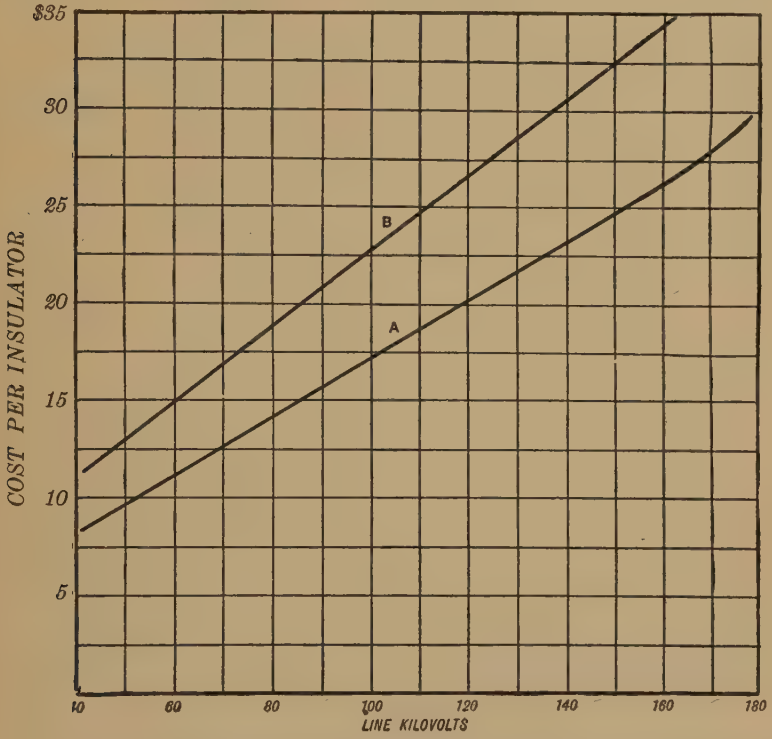


FIG. 118.—Estimating cost of porcelain suspension insulators. (A) Standard 9,000 lb. tensile. (B) High strength, 18,000 lb. tensile.

of the structures any appreciable bearing. The heavy anchor and dead-end towers are, of course, built up from the foundations; other towers are assembled and hoisted by use of a motor lorry and shear legs.

For the type of line under review the following costs are not unusual in fairly good country:

TABLE 64.—*Unit Construction Labor Costs for the 150-kilovolt Line.*

Work.	$ per tower.
Distributing material	50
Excavation and backfill	40
Erecting towers	75
Stringing wire, copper	25
Stringing wire, aluminum-steel	30
Cleaning up and special work	5

From these figures the cost per mile is readily derived by reference to the average span in either case. It will be seen that the cost of handling the reinforced conductor is slightly higher than that for copper, because of the additional time to make up dead ends.

TABLE 65.—*Summarized Estimates for the 150-kilovolt Transmission Line.*
(*Dollars per mile.*)

	Copper.	Aluminum-Steel.
(A) RIGHT-OF-WAY	$ 5,000	$ 5,000
(B) CONSTRUCTION COST:		
(1) *Labor:*		
(11) Distribution	365	270
(12) Excavation	292	216
(13) Setting towers	546	405
(14) Stringing wire	183	162
(15) Cleaning up	37	27
(16) Special work	—	—
TOTAL LABOR (B, 1)	1,423	1,080
(2) *Material:*		
(21) Tower steel	3,442	3,241
(22) Conductors	4,004	4,226
(23) Ground wires	—	—
(24) Insulators	1,655	1,200
(25) Hardware	80	135
(26) Cement	50	50
(27) Other material	—	—
TOTAL MATERIAL (B, 2)	9,231	8,852
TOTAL CONSTRUCTION COST (B)	10,654	9,932
(C) OVERHEAD EXPENSE:		
(1) Engineering and supervision (3 per cent. of B)	302	298
(2) Contingencies (5 per cent. of B)	533	497
(3) Interest (7½ per cent. of A + B)	1,174	1,120
(4) Other charges (10 per cent. of A + B)	1,565	1,493
TOTAL OVERHEAD EXPENSE (C)	3,574	3,408
TOTAL COST OF LINE	$19,228	$18,340

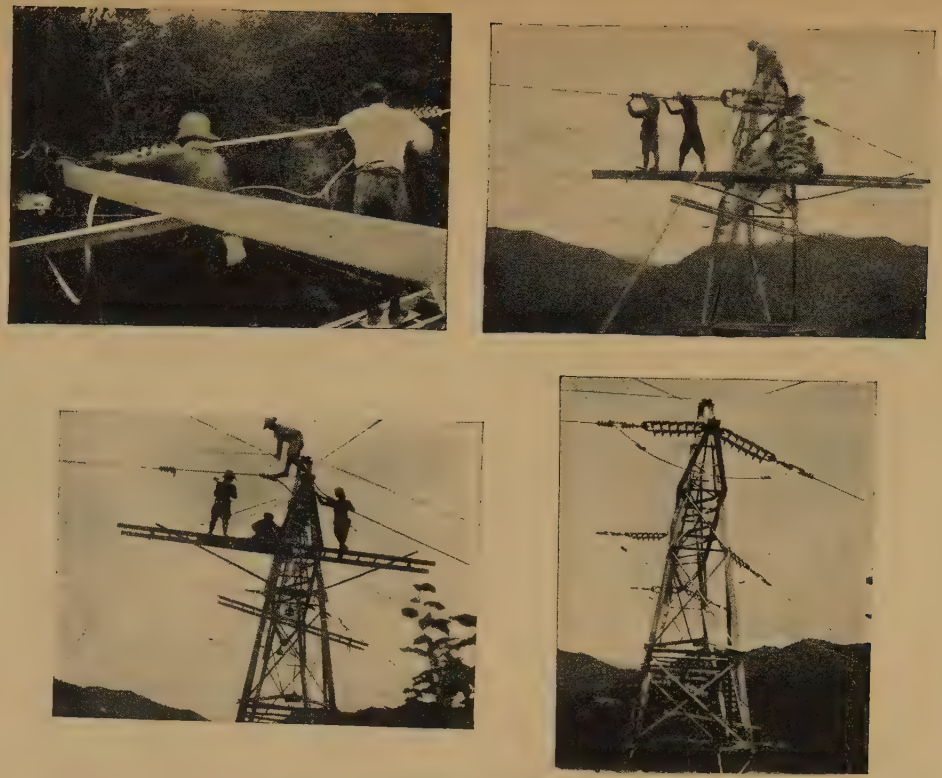


FIG. 119.—FOUR STAGES IN MAKING UP A DEAD END WITH A HEAVY ALUMINUM-STEEL CONDUCTOR.

[*Facing page 304.*

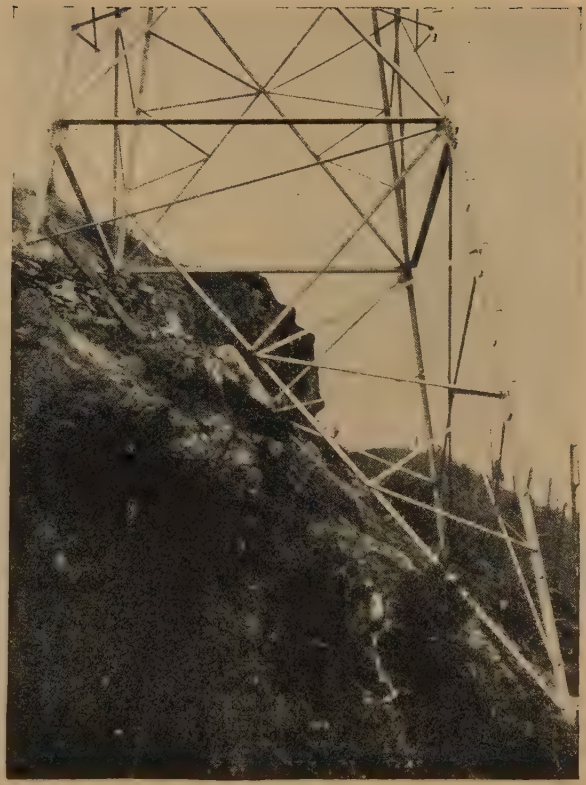


FIG. 120.—SPECIAL FORM OF TOWER EXTENSION FOR A HILLSIDE POSITION.

FIG. 121.—METHOD OF SUBMERGING LOWER MEMBERS OF TOWER TO CORRECT THE EFFECT OF HORIZONTAL REACTION.

[*Facing page 305.*

Certain aspects of the estimate given below call for notice, particularly the relatively low total of labor costs. This is due to the proposed use of mechanical appliances in every way possible for digging holes, hoisting towers, and stringing wire; the size of the crews can, therefore, be kept small, but the items of plant, rental and maintenance help to increase the overhead charges.

The final result shows that for this particular case the line will cost some $888 less per mile if steel-cored aluminum wire is used instead of copper wire of the equivalent size. Obviously, any change in the market conditions assumed will alter this conclusion, which is in no way general. Accepting for the present illustration this 4½ per cent. economy, it remains to be shown whether a still cheaper line cannot be built by maintaining the use of the reinforced conductor and stringing at a different tension. As mentioned earlier, by stringing the line conductors at the maximum permissible tension, the sag will be reduced and the towers spaced out more widely. On the other hand, the test loads on the tower crossarms will be correspondingly heavy, and lead to a greater weight of steel. If the wire is strung at a much lower stress, it becomes necessary to increase the number of supports per mile, but their individual weight is reduced on account of the lower test loads and the lower stress in the wires. The problem of the design is to effect a satisfactory compromise. In the foregoing estimates the maximum stress in the conductors is assumed to be 40 per cent. of the ultimate load. It will, therefore, be of interest to study the effect of a tension 30 and 50 per cent. of the ultimate load respectively.

Stringing curves have been derived for the different conditions allowing for these three different values of maximum stress in the aluminum-steel 415,000 cir. mil conductors, and the template in each case applied to the profile. The summarized results are set out in the accompanying table:

TABLE 66.—*Effect of varying the Stress in the Conductors of the 150-kilovolt Line.*

Percentage of ultimate stress	30	40	50
Actual maximum tension (lb.)	6,300	8,400	10,500
Maximum sag (ft.)	25	25	25
Height of tower, suspension (ft.)	85	85	85
Height of tower, semi-anchor (ft.)	83	83	83
Height of tower, anchor (ft.)	81	81	81
Average span on profile (ft.)	780	980	1,075
Towers per mile	6.76	5.40	4.92

It will be seen that with the lower working stress in the wires the longitudinal test loads on the towers will be reduced, whilst at the same time the shorter span for the same conductor will reduce the transverse and vertical loads. The tower design will, therefore, be appreciably lighter, and by laying out the stresses the actual weight can be estimated. At the same time, the structures to carry the higher working load will have a greater individual weight, and this must also be ascertained.

TABLE 67.—*Weight of Towers for varying Values of Stress in the Conductor.*

	30 per cent. ultimate stress.			50 per cent. ultimate stress.		
Type of tower	Suspension.	Semi-anchor.	Anchor.	Suspension.	Semi-anchor.	Anchor.
Weight (lb.)	6,540	9,300	13,300	8,500	13,000	19,200
Number per mile	6.42	0.23	0.11	4.66	0.17	0.09
Weight per mile (lb.)	41,900	2,140	1,460	39,600	2,210	1,730
Total weight steel (lb.)	45,500			43,540		
Extra steel (5 per cent.) (lb.)	2,270			2,180		
Corrected total (lb.)	47,770			45,720		
Cost at 7¢ lb.	$3,344			$3,200		

From the foregoing figures it is seen that any change in the design which would reduce the stress in the wires will be economically unfavorable. Not only will there be a greater aggregate weight of steel, but it must also be remembered that costs of insulators and labor will be increased on account of the greater number of individual towers. On the other hand, some advantage would appear to be derived from a higher stress in the conductors, as this shows a distinct economy in respect of

tower steel, insulators, and labor. Eliminating the 30 per cent. results (Table 68), compares the costs of the line as strung with aluminum-steel conductors 40 and 50 per cent. tension.

As a result of modifying the working tension in the conductor, it will be seen that a net economy of 1.6 per cent. is realized. This is not a remarkable saving, but is illustrative of the general method for deriving the most economical line design.

It is not, of course, intended to imply that an economic study should be limited to the above procedure. Many other vari-

TABLE 68.—*Estimated Cost of Transmission Line for Two Different Values of Stress in the Conductors.*

Tension in wire.	40 per cent.	50 per cent.
(A) RIGHT-OF-WAY	$5,000	$5,000
(B) CONSTRUCTION COST:		
(1) Labor	1,080	995
(2) Material	8,852	8,696
TOTAL CONSTRUCTION COST (B)	9,932	9,691
(C) OVERHEAD EXPENSE:		
(1, 2) Engineering and contingencies (8 per cent. of B)	795	775
(3, 4) Interest and other charges (17½ per cent. of A + B)	2,613	2,570
TOTAL OVERHEAD EXPENSE (C)	3,408	3,345
TOTAL COST OF LINE PER MILE	$18,340	$18,036

ables may be modified, and a careful estimate prepared in each case to determine the most favorable elements. For instance, all the foregoing calculations have been based on the use of double-circuit rigid-tower construction. There is reason to believe that two lines of single-circuit towers are sometimes more favorable, and in certain circumstances even more economical. A single circuit offers a better opportunity for relieving intermediate structures of broken-wire loads, and so introducing "flexible" construction.

Twin steel poles or concrete poles braced by a crossarm from which the insulators hang in the same horizontal plane are a form of construction which has found application on the 132-

kilovolt system of the Swedish State Water Power Board, and not only has the line operated satisfactorily without failure, but the capital cost is probably the lowest on record for such an important project.

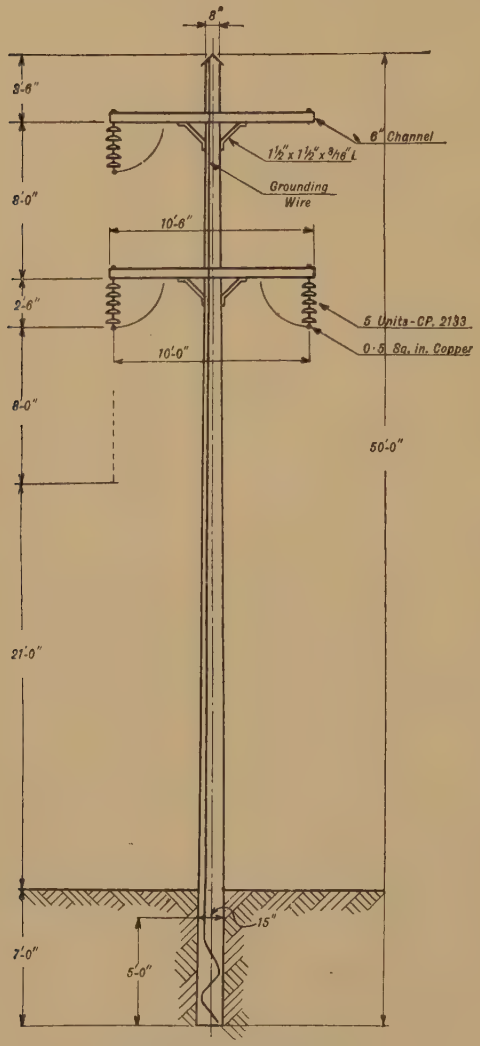


FIG. 122.—Wood pole construction for 66 kilovolts.

Some investigators have attempted a mathematical solution of the economic design problems of transmission line work. The results, however, have not been happy. Despite the complexity of the equations involved, they usually depend upon certain basic assumptions chosen for simplicity. In all cases which have come to the attention of the author these assumptions could not be reconciled with practical conditions. There would appear to be no short cuts in solving the problem of laying out the cheapest transmission line to satisfy the required conditions, except to draw up a group of designs and eliminate all but the most satisfactory.

It is obvious that many sparsely settled communities may pro-

vide a profitable field for the sale of electrical energy, but will in no wise be able to carry the fixed charges on a transmission line costing $20,000 per mile. In such a case a substantial wood pole line operating at about 66 kilovolts would provide service until the load built up to justify greater capital outlay. It may be of interest to estimate the approximate first cost of such a line as indicated. The main particulars of the installation are tabulated below:

TABLE 69.—*Data of 66-kilovolt Pole Line for Transmitting 20,000 kva. Fifty Miles, Single-Circuit.*

CONDUCTORS:	
Size (copper) (cir. mils.)	190,000
Stranding	7 × 0.165
Weight per 1,000 ft. (lb.)	595
Maximum sag on 300-ft. span (ft.)	8
Maximum tension (lb.)	3,250
INSULATORS:	
Number of discs	5
Length of string (in.)	28
POLES:	
Diameter at top (in.)	7½
Diameter 5 ft. from butt (in.)	14
Length of pole (ft.)	50
Depth of foundation (ft.)	7
Number of poles per mile	17.6

The use of single poles is dictated by reasons of economy, and while twin poles would give greater strength and yield a wider crossarm spacing, the single poles adopted will have a sufficient safety factor and, at the same time, will require the minimum width of right-of-way. High-tension pole lines of this character are in many parts of the world constructed along the roadside in rural districts, a permit being granted by the local authority in consideration of a fair rental. However, where the wayleaves must be obtained on private property, a mutually fair agreement should be possible, because of the very small disturbance necessary for a single-pole setting.

In such a design as this a standard length and weight of pole is used throughout the line. Where heavier loads are encoun-

tered due to change in alignment, the span is shortened so as to maintain a constant bending moment at a safe figure. For dead-ending, four poles will generally be built up to take the strains. A definite amount of guying is, of course, necessary where considerable angles must be turned, as well as on sloping ground. A good many of the difficulties of uneven country are eliminated on a steel tower line, because it is possible to skip over many irregularities. On a pole line, due to the necessarily shorter span, these must all be met and negotiated. Head guying is, therefore, necessary on steep slopes, and side guying at sharp turns, leading to increased costs for labor, steel guy wire, and anchors.

TABLE 70.—*Summarized Estimates for 66-kilovolt Wood Pole Transmission Line.* (*Dollars per mile.*)

	Quantity.	Unit price.	Total.
(A) RIGHT-OF-WAY (including surveys and clearing)	1 mile.	—	$1,250
(B) CONSTRUCTION COST:			
(1) *Labor:*			
(11) Distribution	1 mile.		25
(12) Excavation	"		35
(13) Setting poles	"		125
(14) String wire	"		150
(15) Cleaning up	"		15
(16) Special work	"		25
TOTAL LABOR (B, 1)	—		375
(2) *Material:*			
(21) Poles	18	25	450
(22) Crossarms and braces	18	6	108
(23) Conductors	9,420 lb.	16¢	1,480
(24) Insulators	60	10	600
(25) Guy wire and anchors	—		25
(26) Hardware	—		250
(27) Other material	—		100
TOTAL MATERIAL (B, 2)	—		3,013
TOTAL CONSTRUCTION COST (B)	—		$3,388
(C) OVERHEAD EXPENSE:			
(1, 2) Engineering and contingencies (8 per cent. of B)	—	—	271
(3, 4) Interest and other charges (17½ per cent. of A + B)	—	—	811
TOTAL COST PER MILE OF LINE			$5,720

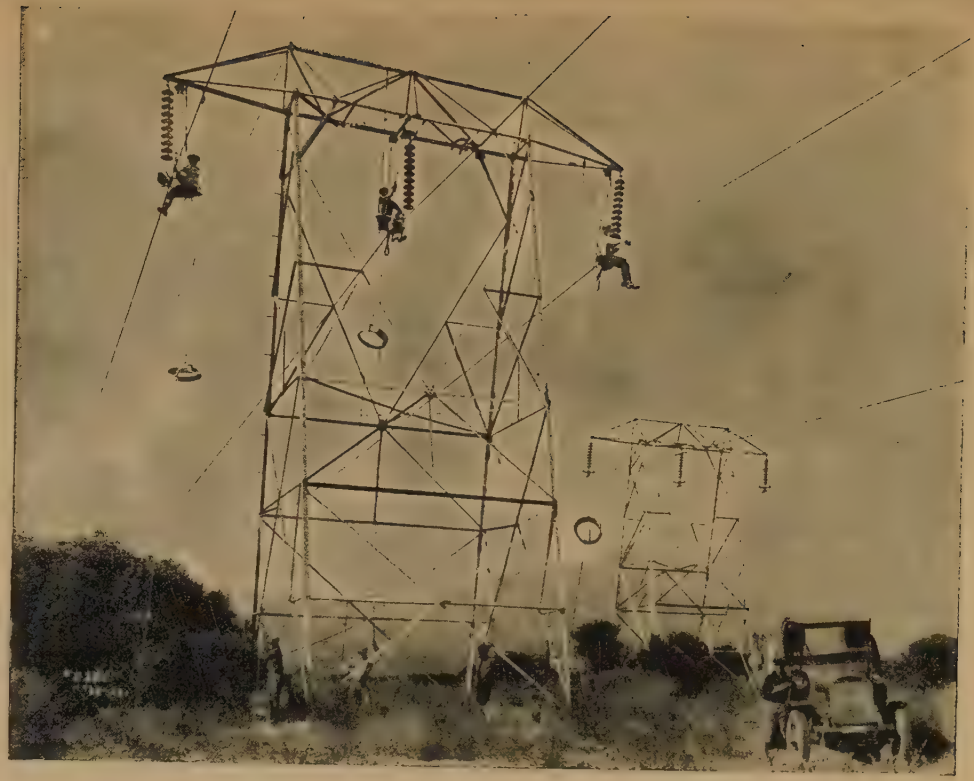


FIG. 123.—INSTALLING INSULATORS AND SHIELD RINGS ON A 220-KILOVOLT LINE.

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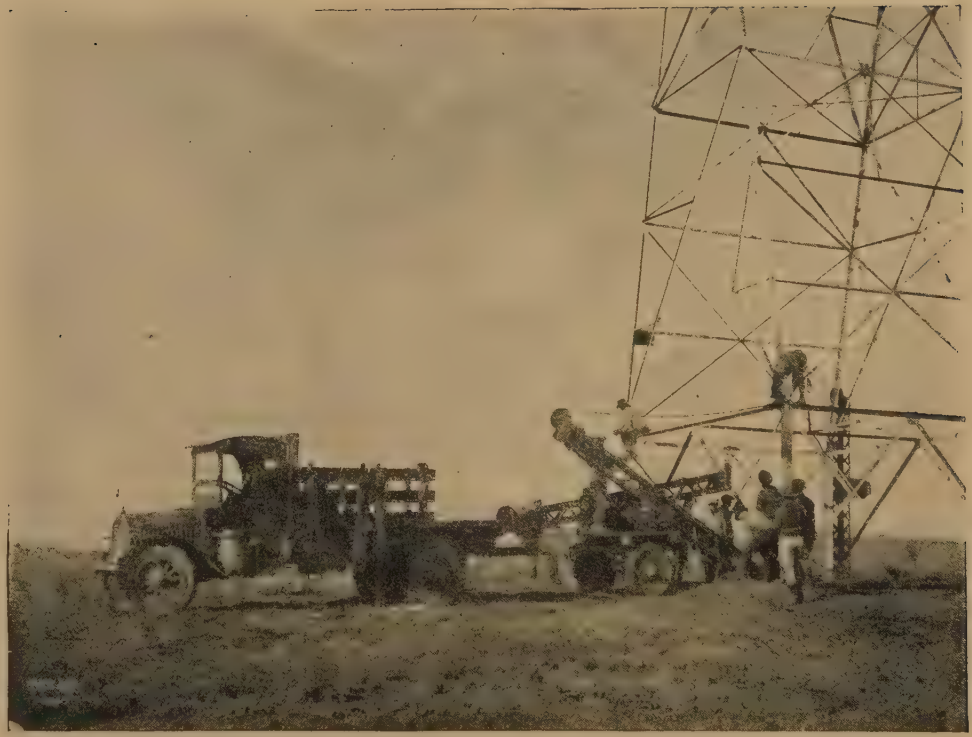

FIG. 124.—TOWER RAISED 10 FEET BY THE INSERTION OF EXTENSION POSTS. REMOVING THE JACKS AND TACKLE.

[*Facing page 311.*

Steel channel crossarms are used because of their long life. This necessitates the use of five suspension insulator units instead of four, as is customary with wood crossarms. A galvanized steel grounding wire is run from the shed at the top of the pole to the foot of the foundation, and is connected to each crossarm. As regards the cost of the line, the following represents figures which have been realized in recent practice. These are intended to serve simply as an illustration, and can obviously have no general application.

This probably represents the lowest figure for which a substantial pole line can be built to operate with reasonable reliability under the standard values of loading and safety factor. Comparing this with the 150-kilovolt tower line already considered, the relative capacity of the two installations will be 20,000 and 100,000 kva. for similar conditions of load, whilst the capital cost amounts to $5,720 and $18,340 respectively, so that the cost per kilowatt capacity becomes approximately 29c and 18c per mile respectively. The tower line will also have lower depreciation and maintenance charges to compound.

Opportunities are not available for varying the economic factors of a pole line in the same way as with steel towers, because in the latter case the structures are designed especially for the job, whereas the wood pole must be used in the sizes in which it comes. If the wire were strung with a higher stress, the sags would be reduced, but probably not enough to use the next shorter length of pole, and at the same time heavier guys and struts would be necessary at corners and dead ends. For a large size of wire (*e.g.*, above 100,000 cir. mils) the use of a maximum stress value of 40 per cent., together with 500-foot poles and a span of 300 to 400 feet, will probably give the best compromise.

Economic Tendencies.—No reference has been made to the operating voltage as a factor in the first cost or operating charges of the line. It is not strictly possible to compare the estimates for a given line as designed for different voltages, because the capacity per circuit will, as already seen, appreciates

very considerably with the higher potentials. For pressures lower than 100 kilovolts, increase in voltage will, of course, result in a distinct economy of conductor material, whether of copper or aluminum, and as this is the largest single item of construction in lines of this group, the saving is very significant. For the transmission of a given amount of power, which is the manner in which the problem is usually presented, the range of appropriate working voltage is relatively narrow. Nor does the distance of transmission form the main factor in the selection of the suitable pressure; the capacity in kilovolt-amperes is the chief element in the matter. When 50,000 kva. or more are to be transmitted over each circuit, no considerable economy of conductors can be realized by an increase in voltage, because reduction in the size of wire will probably lead to energy losses by corona discharge. With the present extension of systems designed to operate at 220 kilovolts, there is a distinct movement toward the use of very large and heavy cables. In addition to this, the cost of insulators is greatly increased as well as that of the towers, on account of the heavy conductors to be carried and the wide spacings necessary. In every way, therefore, it may be said these ultra-high voltages cost more. That they are economically justified is due to the very considerable blocks of power which are demanded of them. In the western United States cities are rapidly growing from 250,000 to one million population, with a connected load approximating to 1 kilowatt per person. Since the greater part of the energy is brought into the city from the mountain water power sites, it is clear that the capacity of every transmission circuit is to be utilized at the maximum. Voltages have, therefore, steadily increased from 50 to 100, and finally to 220 kilovolts, not because of any successively increasing distance of transmission, but simply on account of the growing demand for power.

A marked tendency is in evidence for the cost of high-tension lines to increase. It will be found in comparing recent construction with that prevailing from 1910 to 1915 that it is appreciably heavier and more substantial. A higher factor of

safety is in evidence in line insulation. Loadings which were estimated at from ⅜ to ½ inch ice thickness are now often assumed at from ¾ to as much as 1½ inches. Towers which were originally submitted to a "breast load," putting little or no stress in the diagonals, are now subjected to heavy test pulls at the extremities of the crossarms so that the maximum torsion results. Lastly, the practice of stringing the line with conductors of reinforced cables offers in itself a greater safety factor in that sags are reduced, whipping is largely eliminated, and little or no burning off occurs, even with a heavy arcing ground.

The conclusion to be drawn from this is that the transmission line is coming to be recognized as in no wise the least important engineering element in a power system, and that the transmitting of 100,000 kilowatts or more over a single circuit at 150 kilovolts or higher is an engineering problem differing not only in magnitude, but in elementals, from the duties demanded of the single-pole lines with which the art was initiated. Notwithstanding that the investment on transmission equipment has grown to such large dimensions, it will be found that, making proper allowance for depreciation and maintenance, the modern tower line is cheaper in terms of dollars per kilowatt mile than its more primitive predecessors.

A more important development has been due to the wide adoption of the synchronous condenser as an essential part of the equipment of the receiving station. Not only does the condenser assist in stabilizing the operating conditions of the modern long-distance transmission line, but it virtually eliminates power factor problems, and so directly increases the power capacity of the installation. The economic bearing of this is that two circuits will suffice for the load, which, without synchronous condensers, would require three; the investment per kilowatt-mile is, therefore, reduced.

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